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PROJECT WISH: THE EMERALD CITY

PHASE II

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ABSTRACT

The purpose of the Permanently Manned Autonomous Space Oasis, designated Project WISH: The Emerald City, is to serve as permanent living quarters for space colonists. In addition, it will serve as a stopover for space missions and will be capable of restationing itself practically anywhere within the solar system to provide support for these missions. The station should be self-sufficient, with no specific dependence on any resources from Earth.

The 1990-1991 design team continued work started by last year's class. This year, further studies were conducted in the areas of orbital mechanics, propulsion, attitude control, and human factors. Critical elements were identified in each of these areas, and guidelines were established for the design of the Emerald City. Using the knowledge gained from these studies, two particular missions of interest, a Saturn Envelope mission and an Earth-to-Mars mission, were examined. The size and mass estimates, along with the methodologies used in their determination, are considered to be the main accomplishments of Phase II.

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Finally, we would like to mention the students who took part in the design class during the winter quarter. These people were Tim Chu, Doug Gulick, Patrick Plaisted, Keith Rabe, Richard Taylor, and Cathy Trenta.

FOREWORD

This report reflects the result of our design classes through the second year of Project WISH. The design activity was carried out through a sequence of three courses offered during the autumn, winter, and spring quarters. The autumn quarter course was a technical elective, two credit-hour, introductory course, mainly dedicated to the understanding of the accomplishments of the first phase (1989-1990) of the project and building the background to be able to further the design. The winter quarter course fulfilled a four credit-hour design course requirement for the seniors. During the autumn and winter quarters, seminars by NASA Lewis personnel were included. The spring quarter class was a three credit-hour technical elective course which culminated in this report. Project WISH is measuring up to our expectations in every regard both in technical and educational aspects.

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NOMENCLATURE

Greek

β - thrust angle
 γ - true anomaly
 Δ - change in
 Θ - orientation from inertial reference axes
 μ - gravitational parameter, $1.3271544 \times 10^{11} \text{ km}^3/\text{s}^2$
 π - 3.141592653
 ρ - density
 σ - stress
 τ - period, non-dimensional time
 Ω - orbital angular velocity

Latin

D - diameter
F - force
I - impulse, moment of inertia
J - impulse
N - number of crewpeople
P - pressure, power
R - ratio of thrust to gravity force, major radius of torus
TOF - time-of-flight
V - velocity, volume
X - inertial reference axis
Y - inertial reference axis
a - acceleration
g - gravitational constant on surface of Earth, 9.81 m/s^2
h - height, orbital angular momentum
m - mass
m - mass flow rate
n - number of engines, torus spin rate
r - radius
t - time, thickness
x - state vector

Subscripts

RMS - root-mean-square
T - total
atm - atmosphere
c - cavity
con - for control
dry - dry (without propellant)
f - final state
ff - free-flight
i - initial, individual
l - payload

Subscripts (continued)

max - maximum
min - minor
p - propellant
pr1 - first powered flight
pr2 - second powered flight
sp - specific
spe - engine specific
syn - synodic
th - thrust
u - uranium
w - engine
0 - starting state
1 - first state
2 - second state

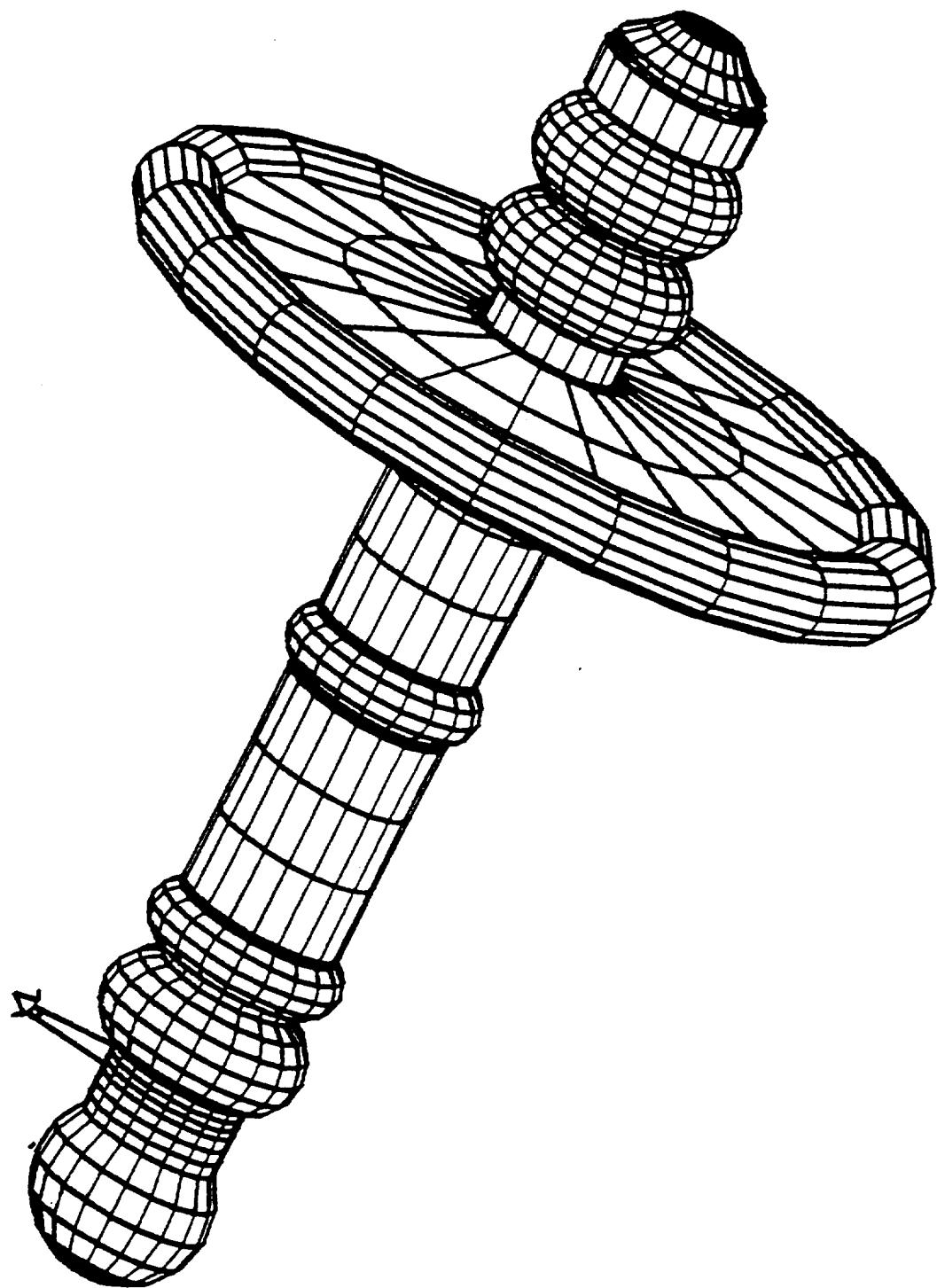


Figure 1.1 - The Emerald City

CHAPTER 1

INTRODUCTION

1.0 PROJECT OVERVIEW

The year is 1620. Winter has struck with a vengeance on the Northeastern coast of the New World. The one hundred and two Pilgrims that have made the journey across the great expanse of the Atlantic Ocean are fighting for their lives. Because there was not time to establish themselves firmly on the shore, the Pilgrims are forced to take shelter on the Mayflower, the ship that brought them across the ocean, for survival. Although some will be lost, those that endure through the first harsh winter will do so because of the support of their ship. With this support, so critical during the initial months of the settlement, the Pilgrims will survive until the spring and establish a permanent colony in the unexplored land of North America.

The year is now 2060. The first manned mission is arriving at the great ringed planet, Saturn. The purpose of this mission is to investigate the Saturnian moon Titan, an object of man's curiosity ever since the Cassini probe first explored it back at the turn of the century. It appears that the speculation about the possibility of colonizing Titan, which started as far back as the 1990's¹, will finally be either proved conclusively or scrapped with the other concepts that never fulfilled their potential. Limitations of the interplanetary ship carrying the expedition have made cargo space precious. Excess amounts of food and supplies have been sacrificed

to accommodate the extensive scientific and data gathering equipment needed to thoroughly explore Titan and the other diverse moons of Saturn. Because of this, the Emerald City has taken up station outside of Saturn's sphere of influence to provide assistance for this historic mission. It will furnish food and equipment for the astronauts, as well as a place for them to take refuge from the desolate vacuum of space. It can also furnish an environment simulating that of Earth, providing artificial gravity as well as the psychological benefits of a large group of people, points which their own ship could not address. Because of the presence of the Emerald City, the mission can remain at Saturn for a much longer period of time. With the extra data that could be collected and recorded, future missions to the moons of Saturn may be made with more confidence, perhaps with the intent of establishing a permanent settlement on Titan.

What is the connection between these two events, separated by over 400 years? The success of both of these scenarios is dependent upon the support provided by the ships in order to make it through the difficult initial stages of their missions. Without this initial support, both missions would be in serious jeopardy. This discussion of past and future events sets the stage for the introduction of Project WISH.

1.1 PROJECT DESCRIPTION

Project WISH (Wandering Interplanetary Space Harbor) is a three year design project currently being conducted at The Ohio

State University. This project deals with the design of a Permanently Manned Autonomous Space Oasis, designated Emerald City (see Figure 1.1). The purpose of Project WISH and the Emerald City is to serve as permanent living quarters for between 500-1000 space inhabitants and to provide crucial support for interplanetary missions in the solar system. To provide this support, the Emerald City will have the ability to relocate itself virtually anywhere in the solar system. This relocation should be accomplished in periods of three years or less whenever possible, thus making the Emerald City flexible in its mission planning. It also should have a lifetime of fifty years, making it an essential link in the space transportation network throughout the latter half of the 21st century.

During the 1990-1991 academic year, Phase II of Project WISH was carried out. Phase I, conducted during the 1989-1990 academic year, was a general level study of the major systems required for the Emerald City. During Phase II, a more in-depth study was conducted into the disciplines of orbital mechanics, propulsion, attitude control, and human factors. Critical elements were identified in all of these areas, and guidelines were established for the design of the Emerald City. These guidelines were then combined to carry out the design of two particular missions of interest, a Saturn Envelope mission and an Earth-to-Mars mission. The size and mass estimates of the Emerald City for these missions, along with the methods used to obtain them, are considered the main accomplishments of Phase II, and are the focus of this report.

CHAPTER 2

ORBITAL MECHANICS

2.0 INTRODUCTION

Orbital mechanics is a central discipline in space design, and was one of the areas studied in-depth during Phase II of Project WISH. In general, orbital mechanics deals with the motion of a smaller body, broadly termed as the "satellite", in the gravitational field of a larger body, known as the "central body". In the context of Project WISH, this deals with the motion of the Emerald City in the gravitational field of the sun. Orbital mechanics is used to find the velocity changes, or ΔV 's, that are needed for the Emerald City to make a transfer from one place in the solar system to another in a certain time. Last year, some preliminary mission analysis was conducted in an ad hoc manner as an understanding of the computer programs used in the investigation was developed². A preliminary nominal orbit was chosen at 3.2 AU's, but this value was selected due more to the proximity of the asteroid belt than a detailed study of orbital mechanics. Using the experience gained during last year's design effort, a more rigorous study was performed on the transfers for the Emerald City, with the hope that a more substantiated nominal orbit could be chosen. This nominal orbit should yield the most advantageous transfers to as many of the planets as possible. After all, the W in WISH stands for "Wandering", and that is what the Emerald City will be doing throughout the solar system.

2.1 NOMINAL ORBIT

2.1.1 Background

One of the main goals set down for Project WISH this year was the determination of a nominal orbit in heliocentric space. This nominal orbit would act as a sort of "home base" for the Emerald City, a place where it could return between missions for rest and refit. The original design requirement for the project called for a maximum flight time of three years from this chosen orbit to any planet in the solar system. The idea was to make the Emerald City mobile enough to be able to react to orders requiring its presence at a certain planet within a reasonable time frame. However, it was quickly discovered that this requirement placed an untenable burden on the prospective propulsion systems of the Emerald City, even extrapolating well into the 21st century. Thus the design goals were pared down (increasing the flight times to some planets while eliminating trips to other planets altogether) in order to make them more attainable for the time frame being considered.

In the selection of the nominal orbit, an attempt was made to keep the flight times to a minimum while retaining as much of the solar system as possible in the "flight envelope". After much discussion, a new set of design goals emerged for the orbital mechanics and propulsion groups of Project WISH. First of all, it is assumed that the Emerald City will become operational sometime in the mid-21st century. At this time, it is envisioned that humans have become firmly established on the Moon and Mars, and are beginning to look beyond. The next logical step could perhaps be human

exploration of the asteroid belt and the moons of Jupiter. Using such a scenario as background, all of the planets in the solar system were categorized by their perceived importance to humankind's exploration of the solar system in the mid-21st century. These categories were employed as a guide in the decision-making process of what the nominal orbit should be and how much thrust the propulsion system of the Emerald City would need to provide.

The first category is made up of the planets considered very important and consists of Earth, Mars, and Jupiter. These planets would more than likely be the focus of the space exploration effort during the next century. As mentioned earlier, colonies should already be established on the Moon and Mars, and intensive scientific study with preliminary exploration could be taking place on Jupiter and its moons. Thus, the Emerald City's ability to reach them in three years or less would be essential to provide support to these colonies and/or exploration missions. The second category is planets deemed important and is made up of Venus, Saturn, and Uranus. These are planets that would be targets for scientific study, but are not considered as crucial as the planets in the first category. Thus, it was decided that for these planets, transfers of up to five years would be allowable. The third and final category is planets considered to be of least interest, and includes Mercury, Neptune, and Pluto. While these planets have much to offer in terms of scientific value, it was felt that in the time frame of Project WISH, there would be little need for trips to these planets by a spacecraft like the Emerald City. Thus, the

only trips made to these planets would be in special cases when the planets would lie in a favorable orientation with the Emerald City.

By using the above criteria, the design goals given at the beginning of last year were adjusted to more reasonable levels. Instead of requiring the Emerald City to make transfers from the nominal orbit to any planet 100% of the time in three years, this requirement was only applied to the planets in the very important category (Earth, Mars, Jupiter). For the planets in the important category (Venus, Saturn, Uranus), these requirements were eased somewhat by allowing transfers up to five years if necessary, and by not requiring the Emerald City to make the transfer 100% of the time. The design goal would instead be that the Emerald City should be able to make the transfer as much of the time as possible and still keep the propulsion system requirements somewhat reasonable. For the third category (Mercury, Neptune, Pluto), there were no specific design goals set; any transfers that would be possible in less than five years would be considered icing on the cake. Thus, with the above criteria established, the mission analysis was carried out.

2.1.2 Mission Analysis

The main difficulty in the mission analysis portion of Project WISH is the lack of a particular mission to analyze. By definition, the Emerald City is to have the capability to travel wherever it may be needed in the solar system within a reasonable time period. For example, if some crucial product is required for

a fledgling colony on a Jovian moon, the Emerald City will not have the luxury of waiting years for the opening of a launch window to Jupiter before leaving the nominal orbit. Instead, it must be able to make the transfer immediately, regardless of where the planet might be with respect to the Emerald City. This so-called "transfer-on-demand" results in high ΔV 's, which is the amount of velocity change that must be provided to the Emerald City in order for it to achieve a transfer from the nominal orbit to a planet. In turn, this high ΔV places a considerable burden on the propulsion system of Project WISH. Thus, it is hoped to keep these mission ΔV 's down to reasonable values in order to alleviate some of the propulsion problems associated with large velocity changes (see Chapter 3).

Hence, the question arises as to how to perform the mission analysis for the Emerald City. An ad hoc approach of picking target planets and launch dates for sample cases was discussed, but was ruled out due to its lack of rigor and tedious nature. Instead, a methodology was established that allowed a more thorough investigation of the transfers between a nominal orbit and the planets in the solar system to be performed. This methodology is based on a concept known as the synodic period between two orbiting bodies (see Figure 2.1). The synodic period is the time it takes for a certain angular orientation known as the phase angle between two bodies to repeat itself. For example, as shown in Figure 2.1, at some time $t = 0$, the Emerald City and the target planet will lie in a straight line connecting the two to the sun. At this point, the

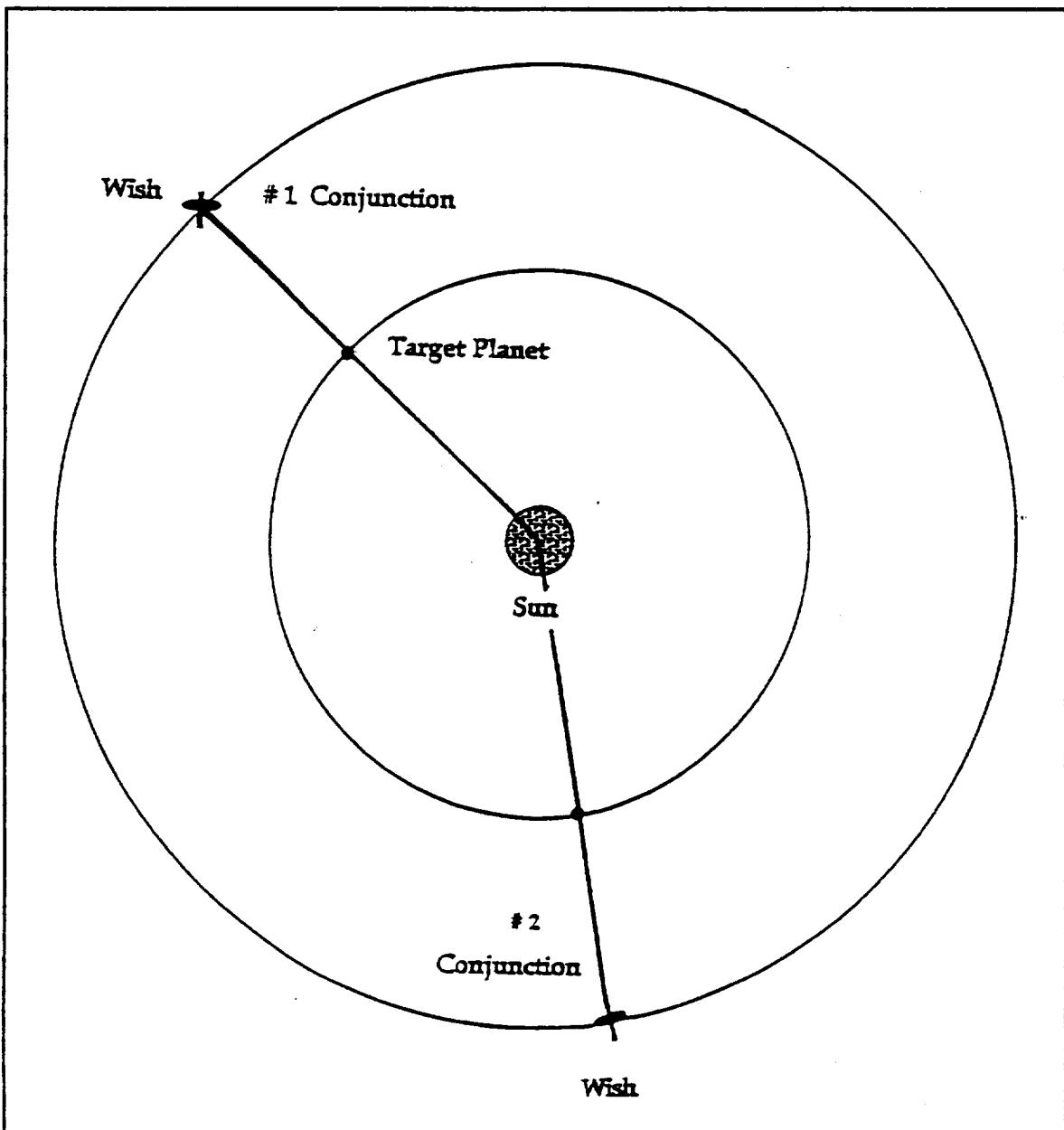


Figure 2.1 - The Synodic Period

phase angle between the two is zero, which is known as conjunction. However, the Emerald City will be travelling slower than the target planet due to the fact that it lies further from the sun. Thus, at a future time, the target planet will essentially "lap" the Emerald City and they will once again be in conjunction at some new posi-

tion in their orbits. The time it takes for this to occur is the called the synodic period, and is denoted by τ_{syn} . The synodic period is related to the angular velocities of the two bodies, Ω_{PC} and Ω_{P} , and is given by

$$\tau_{\text{syn}} = \frac{2\pi}{|\Omega_{\text{P}} - \Omega_{\text{PC}}|}. \quad (2.1)$$

Since the synodic period represents the time it takes for a phase angle to repeat itself, it can be extremely helpful in the mission analysis. Because the ΔV required to make a heliocentric transfer between two bodies in a given time is a function of the orientation of the bodies, it will be nearly cyclic in time, with a period that is given by the synodic period. Thus, instead of looking at transfers throughout the entire fifty year time period that the Emerald City is envisioned to be operating in, they can be examined over a single synodic period. This will result in values for ΔV that can be applied to the transfer at any future time. There are two assumptions on the geometry of the orbits that were made in the statement that the ΔV was cyclic with time. The first assumption is that the orbits of the planets are circular instead of elliptical, while the second assumption is that the nominal and planetary orbits all lie in the same plane. If these assumptions were invalid, then the ΔV would not be cyclic with time as was stated, but would depend on where the planet is located in its orbit. It can be seen from Table 2.1³ that, while these assumptions are not perfect, they are adequate for this preliminary investigation for all of the planets except Mercury and Pluto.

Table 2.1 - Eccentricity and Inclination of the Planets

Planet	Eccentricity	Inclination
Mercury	0.21	7.0°
Venus	0.01	3.4°
Earth	0.02	0.0°
Mars	0.09	1.9°
Jupiter	0.05	1.3°
Saturn	0.05	2.5°
Uranus	0.05	0.8°
Neptune	0.01	1.8°
Pluto	0.26	17.1°

Eccentricity = 0 ==> circular orbit

Inclination = 0° ==> same orbital plane as Earth

Using the computer program MULIMP⁴ obtained from NASA Lewis Research Center and a simple code written to calculate the synodic periods for a given nominal orbit radius, the mission analysis for Project WISH was conducted. MULIMP is a FORTRAN code that calculates the ΔV required for interplanetary transfers under the assumption that the change in velocity takes place instantaneously, i.e. infinite acceleration. Again, this assumption should not hamper the study because the propulsion system powered-flight times should be sufficiently short with respect to the overall flight time to keep this assumption valid for this precursory investigation. The steps in the mission analysis then proceeded as follows. First, a nominal orbit radius was chosen and input into

the code which calculated the synodic periods for this case. Then, MULIMP was run for each planet at many different launch dates (typically between 100 and 200) over a synodic period and for flight times of one to five years in order to obtain the relationship between the ΔV , the flight time, and the fraction of time into the synodic period that the launch occurred at. This resulted in graphs similar to the one shown in Figure 2.2. This particular graph is for a transfer from a nominal orbit of 3 AU's (astronomical units, 1 AU is distance from Earth to Sun) to Jupiter. It can be seen how the ΔV varies over the synodic period; at some points it is relatively low while at other points, it is quite high. It can also be seen that at the completion of one synodic period, the ΔV is nearly the same as it was at the beginning, as expected. The small difference can be attributed to the two assumptions that were made about the geometries of the orbits. While these assumptions were made to facilitate the analysis, MULIMP uses the actual orbits of the planets, complete with eccentricity and inclination. Thus, the ΔV at each of the endpoints of the synodic period does not match exactly, but the fact that they are so close is a good indication of the validity of the assumptions.

To plot out and analyze graphs such as Figure 2.2 for all of the planets at each nominal orbit considered would be quite tedious. Then, the question would be what would one do with the piles of graphs that had been generated. To aid in the analysis of the data obtained from MULIMP, a program was written that would

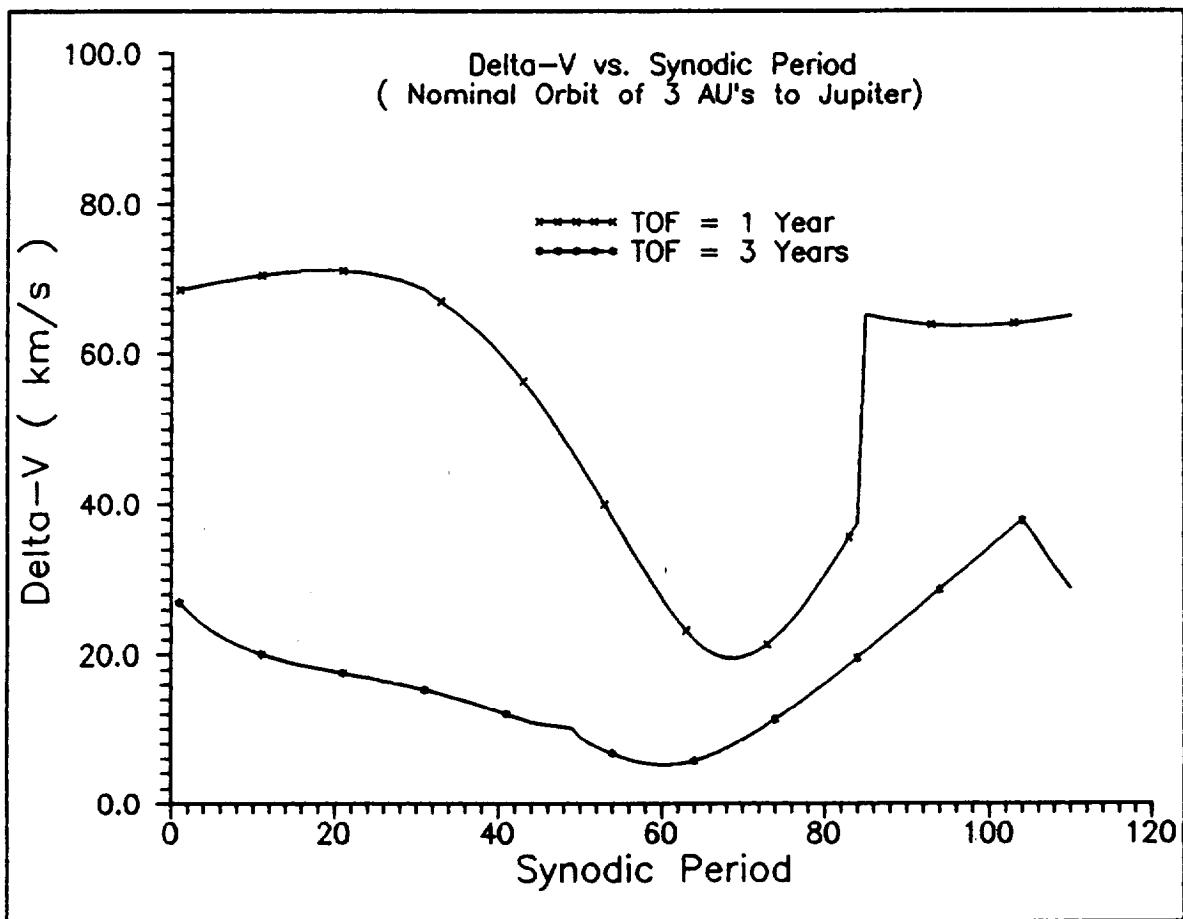


Figure 2.2 - ΔV Behavior Over One Synodic Period
(Flight Time is a Parameter)

calculate the percentage of time during the synodic period that a transfer from a nominal orbit to a planet would fall beneath a certain value of ΔV . Then, this data could be presented in the form of a chart, as shown in Table 2.2. The left-hand side of the chart shows what nominal orbit was used, to what planet the transfer was made, and what was the flight time used. For example, in Table 2.2, N3-P5-T3 would mean a transfer from a nominal orbit of 3 AU's to Jupiter (planet #5), with a flight time of three years. The numbers on the right of the chart represent the percentage of time during a synodic period that a transfer falls

**Table 2.2 - Percentages When Transfer is Possible Given ΔV Limit
(Middle Seven Planets, Nominal Orbit = 3 AU)**

Case	ΔV	10	20	30	40	50	60	70	80
<hr/>									
N3-P2-T1	0.0	16.5	38.8	56.5	71.4	85.1	97.6	100	
N3-P2-T2	0.0	9.4	33.3	49.8	64.7	78.0	91.4	100	
N3-P2-T3	0.0	0.0	26.3	44.3	59.2	73.7	87.5	100	
N3-P2-T4	0.0	0.0	20.4	40.0	56.1	70.6	84.3	98.8	
N3-P2-T5	0.0	0.0	18.0	36.5	52.9	67.8	82.4	97.6	
OPTIMAL FLIGHT TIME = 1.122									
N3-P3-T1	0.0	25.6	50.2	70.0	85.0	98.2	100	100	
N3-P3-T2	0.0	28.6	48.0	64.3	78.0	91.6	100	100	
N3-P3-T3	0.0	18.1	40.5	57.3	72.7	86.8	100	100	
N3-P3-T4	0.0	8.8	34.8	52.9	68.3	83.7	99.1	100	
N3-P3-T5	0.0	0.0	31.3	49.3	65.6	81.5	96.9	100	
OPTIMAL FLIGHT TIME = 1.394									
N3-P4-T1	0.0	31.5	57.0	85.6	96.3	100	100	100	
N3-P4-T2	13.7	44.1	60.7	74.1	87.8	100	100	100	
N3-P4-T3	9.3	43.0	61.9	75.6	86.7	98.5	100	100	
N3-P4-T4	0.0	28.1	48.9	63.7	78.5	96.7	100	100	
N3-P4-T5	0.0	29.3	52.6	68.9	81.5	93.7	100	100	
OPTIMAL FLIGHT TIME = 1.764									
N3-P5-T1	0.0	7.3	20.9	29.1	34.5	40.9	92.7	100	
N3-P5-T2	11.8	32.7	83.6	99.1	100	100	100	100	
N3-P5-T3	24.5	70.0	89.1	100	100	100	100	100	
N3-P5-T4	39.1	70.0	87.3	100	100	100	100	100	
N3-P5-T5	40.9	68.2	84.5	100	100	100	100	100	
OPTIMAL FLIGHT TIME = 4.466									
N3-P6-T1	0.0	0.0	0.0	0.0	0.0	0.0	18.7	29.0	
N3-P6-T2	0.0	0.0	8.8	34.7	49.2	100	100	100	
N3-P6-T3	0.0	18.1	45.6	94.3	100	100	100	100	
N3-P6-T4	0.0	37.8	81.9	100	100	100	100	100	
N3-P6-T5	11.9	57.0	87.0	100	100	100	100	100	
OPTIMAL FLIGHT TIME = 6.860									
N3-P7-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N3-P7-T2	0.0	0.0	0.0	0.0	0.0	0.0	13.8	33.5	
N3-P7-T3	0.0	0.0	0.0	0.0	27.2	48.8	100	100	
N3-P7-T4	0.0	0.0	0.0	35.4	75.2	100	100	100	
N3-P7-T5	0.0	0.0	29.9	69.7	100	100	100	100	
OPTIMAL FLIGHT TIME = 12.960									
N3-P8-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N3-P8-T2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N3-P8-T3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.7	
N3-P8-T4	0.0	0.0	0.0	0.0	0.0	18.8	42.6	91.9	
N3-P8-T5	0.0	0.0	0.0	0.0	26.9	54.3	100	100	

below a certain ΔV . By using charts such as the one found in Table 2.2, different transfer characteristics can be examined quickly and completely, as opposed to a piecemeal approach, which would be time consuming and not as thorough. Thus, now the merits of different nominal orbits can be compared.

2.1.3 Analysis Results

The resulting charts from the mission analysis can be found in Tables 2.3-2.10 for nominal orbits of 3, 4, 5, and 10 AU's. These were broken down into the inner planets in Tables 2.3-2.6 and the outer planets in Tables 2.7-2.10.

**Table 2.3 - Percentages When Flight is Possible Given ΔV Limit
(Inner Planets, Nominal Orbit = 3 AU)**

Case ΔV =	10	20	30	40	50	60	70	80
<hr/>								
N3-P1-T1	0.0	0.0	15.1	31.2	45.2	61.3	76.3	90.3
N3-P1-T2	0.0	0.0	8.6	25.8	39.8	54.8	69.9	86.0
N3-P1-T3	0.0	0.0	3.2	21.5	34.4	50.5	65.6	80.6
N3-P1-T4	0.0	0.0	0.0	18.3	32.3	46.2	62.4	78.5
N3-P1-T5	0.0	0.0	0.0	15.1	29.0	44.1	58.1	76.3
<hr/>								
N3-P2-T1	0.0	16.5	38.8	56.5	71.4	85.1	97.6	100
N3-P2-T2	0.0	9.4	33.3	49.8	64.7	78.0	91.4	100
N3-P2-T3	0.0	0.0	26.3	44.3	59.2	73.7	87.5	100
N3-P2-T4	0.0	0.0	20.4	40.0	56.1	70.6	84.3	98.8
N3-P2-T5	0.0	0.0	18.0	36.5	52.9	67.8	82.4	97.6
<hr/>								
N3-P3-T1	0.0	25.6	50.2	70.0	85.0	98.2	100	100
N3-P3-T2	0.0	28.6	48.0	64.3	78.0	91.6	100	100
N3-P3-T3	0.0	18.1	40.5	57.3	72.7	86.8	100	100
N3-P3-T4	0.0	8.8	34.8	52.9	68.3	83.7	99.1	100
N3-P3-T5	0.0	0.0	31.3	49.3	65.6	81.5	96.9	100
<hr/>								
N3-P4-T1	0.0	31.5	57.0	85.6	96.3	100	100	100
N3-P4-T2	13.7	44.1	60.7	74.1	87.8	100	100	100
N3-P4-T3	9.3	43.0	61.9	75.6	86.7	98.5	100	100
N3-P4-T4	0.0	28.1	48.9	63.7	78.5	96.7	100	100
N3-P4-T5	0.0	29.3	52.6	68.9	81.5	93.7	100	100

Table 2.4 - Percentages When Flight is Possible Given AV Limit
 (Inner Planets, Nominal Orbit = 4 AU)

Case AV =	10	20	30	40	50	60	70	80
<hr/>								
N4-P1-T1	0.0	0.0	0.0	15.2	33.7	51.1	63.0	73.9
N4-P1-T2	0.0	0.0	0.0	27.2	43.5	56.5	66.3	76.1
N4-P1-T3	0.0	0.0	0.0	19.6	39.1	52.2	64.1	73.9
N4-P1-T4	0.0	0.0	0.0	10.9	35.9	48.9	62.0	71.7
N4-P1-T5	0.0	0.0	0.0	8.7	31.5	46.7	59.8	69.6
<hr/>								
N4-P2-T1	0.0	0.0	18.3	41.5	61.0	79.3	95.1	100
N4-P2-T2	0.0	12.2	35.4	53.7	68.3	82.9	96.3	100
N4-P2-T3	0.0	7.3	31.7	51.2	64.6	79.3	93.9	100
N4-P2-T4	0.0	0.0	25.6	45.1	59.8	74.4	89.0	100
N4-P2-T5	0.0	0.0	19.5	41.5	58.5	74.4	89.0	100
<hr/>								
N4-P3-T1	0.0	0.0	27.1	50.7	75.0	93.6	100	100
N4-P3-T2	0.0	29.3	50.0	66.4	81.4	95.7	100	100
N4-P3-T3	0.0	24.3	45.0	61.4	76.4	91.4	100	100
N4-P3-T4	0.0	17.1	40.0	57.1	73.6	87.9	100	100
N4-P3-T5	0.0	10.7	36.4	55.0	70.7	85.7	100	100
<hr/>								
N4-P4-T1	0.0	12.4	34.5	60.2	95.6	100	100	100
N4-P4-T2	10.6	41.6	65.5	85.8	100	100	100	100
N4-P4-T3	7.1	40.7	63.7	77.9	95.6	100	100	100
N4-P4-T4	0.0	31.9	54.0	74.3	94.7	100	100	100
N4-P4-T5	0.0	25.7	54.0	73.5	90.3	99.1	100	100

Table 2.5 - Percentages When Flight is Possible Given ΔV Limit
 (Inner Planets, Nominal Orbit = 5 AU)

Case ΔV =	10	20	30	40	50	60	70	80
<hr/>								
N5-P1-T1	0.0	0.0	0.0	8.8	26.4	37.4	53.8	69.2
N5-P1-T2	0.0	0.0	7.7	23.1	41.8	54.9	69.2	83.5
N5-P1-T3	0.0	0.0	0.0	23.1	40.7	56.0	68.1	81.3
N5-P1-T4	0.0	0.0	0.0	22.0	38.5	51.6	67.0	79.1
N5-P1-T5	0.0	0.0	0.0	17.6	37.4	50.5	64.8	78.0
N5-P2-T1	0.0	0.0	0.0	21.7	40.8	62.5	83.3	100
N5-P2-T2	0.0	2.5	33.3	51.7	68.3	84.2	100	100
N5-P2-T3	0.0	0.8	31.7	50.0	66.7	81.7	97.5	100
N5-P2-T4	0.0	0.0	26.7	46.7	64.2	79.2	95.8	100
N5-P2-T5	0.0	0.0	24.2	44.2	60.8	77.5	93.3	100
N5-P3-T1	0.0	0.0	0.0	28.9	51.1	78.5	100	100
N5-P3-T2	0.0	23.7	46.7	66.7	83.7	99.3	100	100
N5-P3-T3	0.0	25.9	46.7	65.2	80.7	97.0	100	100
N5-P3-T4	0.0	21.5	43.0	62.2	77.8	94.1	100	100
N5-P3-T5	0.0	17.0	40.0	59.3	76.3	91.9	100	100
N5-P4-T1	0.0	0.0	12.2	31.7	52.5	94.2	100	100
N5-P4-T2	0.0	33.8	64.0	84.2	99.3	100	100	100
N5-P4-T3	9.4	41.7	64.0	83.5	100	100	100	100
N5-P4-T4	0.0	37.4	59.7	77.7	97.1	100	100	100
N5-P4-T5	0.0	34.5	56.1	76.3	97.1	100	100	100

Table 2.6 - Percentages When Flight is Possible Given AV Limit
 (Inner Planets, Nominal Orbit = 10 AU)

Case AV =	10	20	30	40	50	60	70	80
<hr/>								
N10-P1-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.4
N10-P1-T2	0.0	0.0	0.0	4.4	22.2	36.7	51.1	68.9
N10-P1-T3	0.0	0.0	5.6	18.9	36.7	53.3	68.9	87.8
N10-P1-T4	0.0	0.0	11.1	28.9	43.3	58.9	76.7	93.3
N10-P1-T5	0.0	0.0	13.3	30.0	45.6	61.1	77.8	94.4
<hr/>								
N10-P2-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.2
N10-P2-T2	0.0	0.0	0.0	17.2	35.3	56.0	76.7	97.4
N10-P2-T3	0.0	0.0	15.5	37.9	57.8	75.9	96.6	100
N10-P2-T4	0.0	0.0	27.6	48.3	66.4	84.5	100	100
N10-P2-T5	0.0	0.0	31.9	51.7	68.1	85.3	100	100
<hr/>								
N10-P3-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.7
N10-P3-T2	0.0	0.0	0.0	22.0	43.3	68.5	95.3	100
N10-P3-T3	0.0	0.0	28.3	50.4	73.2	95.3	100	100
N10-P3-T4	0.0	14.2	39.4	61.4	81.1	100	100	100
N10-P3-T5	0.0	21.3	44.1	64.6	84.3	100	100	100
<hr/>								
N10-P4-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.8
N10-P4-T2	0.0	0.0	0.0	25.9	52.4	87.1	100	100
N10-P4-T3	0.0	0.0	34.7	66.7	94.6	100	100	100
N10-P4-T4	0.0	23.8	53.7	79.6	99.3	100	100	100
N10-P4-T5	0.0	32.0	59.9	83.7	100	100	100	100

**Table 2.7 - Percentages When Flight is Possible Given ΔV Limit
(Outer Planets, Nominal Orbit = 3 AU)**

Case	$\Delta V =$	10	20	30	40	50	60	70	80
<hr/>									
N3-P5-T1	0.0	7.3	20.9	29.1	34.5	40.9	92.7	100	
N3-P5-T2	11.8	32.7	83.6	99.1	100	100	100	100	
N3-P5-T3	24.5	70.0	89.1	100	100	100	100	100	
N3-P5-T4	39.1	70.0	87.3	100	100	100	100	100	
N3-P5-T5	40.9	68.2	84.5	100	100	100	100	100	
<hr/>									
N3-P6-T1	0.0	0.0	0.0	0.0	0.0	0.0	18.7	29.0	
N3-P6-T2	0.0	0.0	8.8	34.7	49.2	100	100	100	
N3-P6-T3	0.0	18.1	45.6	94.3	100	100	100	100	
N3-P6-T4	0.0	37.8	81.9	100	100	100	100	100	
N3-P6-T5	11.9	57.0	87.0	100	100	100	100	100	
<hr/>									
N3-P7-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N3-P7-T2	0.0	0.0	0.0	0.0	0.0	0.0	13.8	33.5	
N3-P7-T3	0.0	0.0	0.0	0.0	27.2	48.8	100	100	
N3-P7-T4	0.0	0.0	0.0	35.4	75.2	100	100	100	
N3-P7-T5	0.0	0.0	29.9	69.7	100	100	100	100	
<hr/>									
N3-P8-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N3-P8-T2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N3-P8-T3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.7	
N3-P8-T4	0.0	0.0	0.0	0.0	0.0	18.8	42.6	91.9	
N3-P8-T5	0.0	0.0	0.0	0.0	26.9	54.3	100	100	
<hr/>									
N3-P9-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N3-P9-T2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N3-P9-T3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N3-P9-T4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N3-P9-T5	0.0	0.0	0.0	0.0	0.0	0.0	19.1	40.4	

**Table 2.8 - Percentages When Flight is Possible Given ΔV Limit
(Outer Planets, Nominal Orbit = 4 AU)**

Case	ΔV =	10	20	30	40	50	60	70	80
<hr/>									
N4-P5-T1		0.0	11.0	18.5	24.0	29.5	36.3	43.8	94.5
N4-P5-T2		12.3	28.1	50.7	99.3	100	100	100	100
N4-P5-T3		22.6	78.8	95.9	100	100	100	100	100
N4-P5-T4		46.6	79.5	94.5	100	100	100	100	100
N4-P5-T5		56.8	80.1	93.8	100	100	100	100	100
<hr/>									
N4-P6-T1		0.0	0.0	0.0	0.0	1.4	16.7	20.8	25.0
N4-P6-T2		0.0	0.0	20.1	32.6	41.7	98.6	100	100
N4-P6-T3		0.0	22.2	45.1	99.3	100	100	100	100
N4-P6-T4		2.1	38.2	94.4	99.3	100	100	100	100
N4-P6-T5		18.8	67.4	96.5	100	100	100	100	100
<hr/>									
N4-P7-T1		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N4-P7-T2		0.0	0.0	0.0	0.0	0.0	0.0	20.3	29.7
N4-P7-T3		0.0	0.0	0.0	0.0	28.4	42.6	100	100
N4-P7-T4		0.0	0.0	5.4	36.5	70.9	100	100	100
N4-P7-T5		0.0	0.0	31.1	73.0	100	100	100	100
<hr/>									
N4-P8-T1		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N4-P8-T2		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N4-P8-T3		0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.1
N4-P8-T4		0.0	0.0	0.0	0.0	0.0	20.2	41.1	94.6
N4-P8-T5		0.0	0.0	0.0	0.0	27.9	49.6	100	100
<hr/>									
N4-P9-T1		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N4-P9-T2		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N4-P9-T3		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N4-P9-T4		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N4-P9-T5		0.0	0.0	0.0	0.0	0.0	0.0	15.4	41.0

**Table 2.9 - Percentages When Flight is Possible Given ΔV Limit
(Outer Planets, Nominal Orbit = 5 AU)**

Case	$\Delta V =$	10	20	30	40	50	60	70	80
<hr/>									
N5-P5-T1		6.2	15.8	18.1	22.6	24.3	29.4	35.0	40.7
N5-P5-T2		15.8	26.6	40.7	100	100	100	100	100
N5-P5-T3		20.9	57.1	98.9	100	100	100	100	100
N5-P5-T4		32.8	87.6	99.4	100	100	100	100	100
N5-P5-T5		64.4	84.7	98.9	100	100	100	100	100
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N5-P6-T1		0.0	0.0	0.0	0.0	12.9	16.3	19.7	22.4
N5-P6-T2		0.0	4.8	22.4	29.3	36.1	97.3	100	100
N5-P6-T3		0.0	23.8	40.1	98.6	100	100	100	100
N5-P6-T4		11.6	36.7	100	100	100	100	100	100
N5-P6-T5		20.4	73.5	99.3	100	100	100	100	100
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N5-P7-T1		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N5-P7-T2		0.0	0.0	0.0	0.0	0.0	0.0	20.3	27.2
N5-P7-T3		0.0	0.0	0.0	0.0	27.8	38.0	100	100
N5-P7-T4		0.0	0.0	8.2	35.4	54.4	100	100	100
N5-P7-T5		0.0	0.0	31.6	65.2	100	100	100	100
<hr/>									
N5-P8-T1		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N5-P8-T2		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N5-P8-T3		0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.1
N5-P8-T4		0.0	0.0	0.0	0.0	0.0	23.1	38.1	60.5
N5-P8-T5		0.0	0.0	0.0	0.0	29.3	47.6	100	100
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N5-P9-T1		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N5-P9-T2		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N5-P9-T3		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N5-P9-T4		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N5-P9-T5		0.0	0.0	0.0	0.0	0.0	0.0	18.0	39.5

**Table 2.10 - Percentages When Flight is Possible Given ΔV Limit
(Outer Planets, Nominal Orbit = 10 AU)**

Case	ΔV =	10	20	30	40	50	60	70	80
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N10-P5-T1	0.0	0.0	0.0	0.0	11.0	14.8	17.4	20.6	
N10-P5-T2	0.0	0.0	20.6	27.1	32.9	41.9	100	100	
N10-P5-T3	0.0	21.3	36.1	67.1	100	100	100	100	
N10-P5-T4	7.7	35.5	94.8	100	100	100	100	100	
N10-P5-T5	17.4	54.2	100	100	100	100	100	100	
<hr/>									
N10-P6-T1	5.2	7.0	7.4	10.0	13.0	13.9	14.3	17.8	
N10-P6-T2	6.5	11.3	14.8	19.1	22.2	27.8	33.0	41.7	
N10-P6-T3	8.3	20.4	27.0	33.5	44.8	100	100	100	
N10-P6-T4	15.7	27.4	35.2	97.0	100	100	100	100	
N10-P6-T5	19.1	34.3	97.0	100	100	100	100	100	
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N10-P7-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N10-P7-T2	0.0	0.0	0.0	0.0	7.8	12.4	15.7	19.0	
N10-P7-T3	0.0	0.0	0.0	15.0	19.6	24.8	30.1	36.6	
N10-P7-T4	0.0	0.0	16.3	22.9	29.4	38.6	100	100	
N10-P7-T5	0.0	10.5	23.5	32.0	87.6	100	100	100	
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N10-P8-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N10-P8-T2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N10-P8-T3	0.0	0.0	0.0	0.0	0.0	0.0	15.5	20.8	
N10-P8-T4	0.0	0.0	0.0	0.0	15.5	22.6	29.2	36.3	
N10-P8-T5	0.0	0.0	0.0	16.7	26.2	34.5	47.6	100	
<hr/>									
N10-P9-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N10-P9-T2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N10-P9-T3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N10-P9-T4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
N10-P9-T5	0.0	0.0	0.0	0.0	0.0	0.0	20.9	29.9	

Inner Planets

After reading the above discussion and examining Tables 2.3-2.6, one might be tempted to arrive at a conclusion similar to the following. "Well, since planet Earth fell into the first category of planets that had to be reached 100% of the time in three years or less, and according to Tables 2.3-2.6, Earth can be reached 100% of the time in three years for ΔV 's greater than 60 km/s, then the propulsion system will have to provide a one-way ΔV of greater than 60 km/s for the design goals to be met." However, upon closer inspection, this conclusion is incorrect due mainly to two reasons. The first reason is that the synodic period of the inner planets are rather low, as can be seen in Table 2.7. They range from about

Table 2.11 - Synodic Periods of the Inner Planets

Planet	Mercury	Venus	Earth	Mars
<hr/>				
τ_{syn} (years)				
n = 3 AU	.25	.70	1.24	2.95
n = 4 AU	.25	.67	1.14	2.46
n = 5 AU	.25	.65	1.10	2.26

one-quarter of a year for Mercury to over two years for Mars. This is a key point in determining what ΔV 's will need to be provided for transfers to these inner planets. Because the synodic period is so short, the Emerald City would pass through the entire period in less than three years time. Thus, the Emerald City would have the luxury of waiting at its nominal orbit for some amount of time

after receiving its orders to move, until the ΔV requirements are sufficiently low to make a transfer possible in less than three years and it would still arrive within three years of the time it received its orders to go somewhere.

For example, say that the Emerald City is in a nominal orbit at 4 AU's from the sun. On February 10, 2051, it receives orders to travel to Earth, and its arrival is required within two years. On February 10, the ΔV required to make a two year transfer at this time is found to be 63.9 km/s, a rather high value that would place a large burden on the propulsion system. So instead, the Emerald City decides to wait at the nominal orbit until July 3, 2051, when the ΔV required to make a one year transfer is only 23.1 km/sec. This value is much more easily obtained by the propulsion system, and the Emerald City arrives at Earth on July 2, 2052, about 222 days ahead of the time it was required to be there. This scenario, calculated using MULIMP, is possible because the synodic period for Earth is only 1.14 years, short enough to allow all of the possible phase angles to present themselves to the Emerald City within the time that it is required for it to make the transfer. Thus, instead of leaving immediately, it can wait for some length of time, and then make a transfer that, even with a shorter flight time, has a lower ΔV because of a more favorable orientation.

The second reason that the percentages that a transfer is possible for a given flight time cannot be taken at face value is because of the following fact. In this analysis, the flight time for each transfer is specified, and the ΔV required to make this

exact transfer is found. One might expect that this ΔV would go down as the flight time is made longer, because of the less demanding duration. In general, however, this is not the case for the inner planets. The optimal flight time (the flight time resulting in the lowest ΔV) for the inner planets is on the order of one to two years. Thus, by forcing a trip to one of these planets in, say, three years, the ΔV required actually increases. This is because the trajectory will not go directly to the target planet, but will stall by taking an indirect route in order for the flight time to be the specified value. This phenomenon can be seen in the following example, predicted by MULIMP. The Emerald City receives orders to proceed to Venus on February 27, 2050, and is ordered to be there within 2.5 years. At this point, if the Emerald City were to try to make a transfer with a flight time of 2.5 years, the ΔV required would be 46.1 km/s. However, by making the transfer in only 2.33 years, the ΔV would only be 18.8 km/s, a much better result.

Thus, because of the nature of the transfers to the inner planets for the two reasons cited above, the actual percentages of time that a flight is possible for a given ΔV is rendered meaningless. Instead, what should be looked at is the lowest ΔV a transfer can be made at all with a flight time of three years minus the synodic period. If a transfer can be made at any point in the synodic period for this flight time, then the transfer can be made 100% of the time. Again using the Earth example, in 1.14 years, all of the phase angles between it and the Emerald City will have

occurred due to the length of the synodic period. Thus, if Earth can be reached any percent of the time in 1.86 years or less with a given ΔV , then it can be said that the transfer can be made 100% of the time in under three years from receiving its orders, because it can wait until the favorable orientation appears.

Outer Planets

The results from the mission analysis for the outer planets (Jupiter to Pluto) can be found in Tables 2.7-2.10 for nominal orbits of 3, 4, 5, and 10 AU's. The investigation of the transfers to the outer planets must be treated differently than to the inner planets because the synodic periods are much longer for the outer planets, as seen in Table 2.12. Because of this, the Emerald City

Table 2.12 - Synodic Periods of the Outer Planets

Planet	Jupiter	Saturn	Uranus	Neptune	Pluto
<hr/>					
τ_{syn} (years)					
n = 3 AU	9.26	6.31	5.54	5.37	5.31
n = 4 AU	24.62	10.98	8.85	8.41	8.27
n = 5 AU	196.66	18.02	12.91	12.00	11.71

will encounter only a fraction of the possible phase angles, and must be prepared to make transfers at less than optimum conditions. Thus, for the outer planets, the percentage of time that a transfer is possible for a fixed ΔV becomes important, a yardstick that different nominal orbits can be measured by.

It should be noted what effect moving the nominal orbit further from the sun had on the ability of the Emerald City to reach the outer planets. As seen in Tables 2.7-2.10, there was little benefit gained by moving the nominal orbit away from the sun, and in some cases, the percentages actually went down. This was an important consideration for the selection of the nominal orbit.

2.1.4 Nominal Orbit Selection

The sample nominal orbits that were examined were at 3, 4, 5, and 10 AU's. After examining the percentage tables generated by MULIMP and some discussion, an orbit at 4 AU's was selected as the preliminary nominal orbit. This selection was based on several factors. The first one is the central location of this orbit between Mars, at 1.5 AU and Jupiter, at 5.2 AU. This orbit puts the Emerald City relatively near to the asteroid belt, where vast deposits of valuable materials can be found, and close to the presumed focal points of interplanetary space activity in the mid-21st century, Mars and Jupiter. From this orbit, a three-year transfer to Jupiter can be accomplished 100% of the time with a one-way ΔV of 40 km/s. Thus, if the goals that were laid down at the beginning of this chapter are to be met, the propulsion system would have to provide at least this much ΔV capability. Also, Venus, Earth and Mars can be reached under ΔV 's of 40 km/s in three years or less, considering the points that were brought up in the discussion of the inner planets previously. Saturn can be reached

nearly 100% of the time at 40 km/s using flight times of three years, which is an added bonus. To reach Uranus with a ΔV of 40 km/s, flight times of four and five years must be used, and, for five years, the transfer is possible only 73% of the time. This was felt to be acceptable, because Uranus fell into the category of planets deemed marginally important for exploration in the mid-21st century. Mercury can be reached 100% of the time if a trip to that planet is required, but Neptune and Pluto cannot be reached at all by transfers with flight times up to five years and a ΔV limit of 40 km/s. Thus, trips to these outer planets would require special considerations, such as somehow refueling part of the way there or increasing the propulsion capabilities. A nominal orbit of 4 AU's also puts the Emerald City within reasonable distance of Earth for communications and emergencies, which is why a larger radius orbit was not selected (the benefits gained by moving the orbit out were generally negligible).

An interesting point that should be brought up when discussing the necessary ΔV that the propulsion system must provide is the return to the nominal orbit. Early in this study, it was generally assumed that accounting for the return trip would roughly double the maximum ΔV that would be necessary. However, upon further investigation, some doubts were raised as to the validity of this assumption. When using the MULIMP code, the orbit of the Emerald City is entered by using the six classical orbital elements; the eccentricity, the semi-major axis, the inclination, the longitude of the ascending node, the argument of the periapsis, and the time

of periapsis passage. For the circular orbits that were examined, there is no periapsis, and the last element is replaced by some value that locates the Emerald City in the orbit at a given time. When going from the nominal orbit to a target planet, the Emerald City will leave from a particular point on the nominal orbit and arrive at the target planet, and the ΔV can be calculated by MULIMP. However, for the return trip, there is nothing that says the Emerald City has to return to a particular point on the nominal orbit. Instead, it is free to return to any point along the nominal orbit. Unfortunately, when the orbital elements are used to define the nominal orbit, a "ghost point" is created that moves around the defined nominal orbit, as if it were a planet in that orbit. If MULIMP were used to figure out a ΔV required for the return trip, it would calculate it as if it had to return to the "ghost point's" location instead of anywhere on that orbit. Because of this freedom, the Emerald City could return to the nominal orbit at the point that would require the least ΔV for the transfer, and the ΔV 's would probably not be as high as originally expected. It was not known if or how MULIMP could be used to calculate the ΔV for a situation like this, so an total ΔV of 50 km/s was assumed as the necessary upper limit to give to the propulsion system. For the inner planets, this figure should be quite adequate due to the Emerald City's ability to make optimal transfers as was discussed above. For the outer planets, it was felt that this figure should result in 100% ability to reach Jupiter and Saturn in three years and above 50% to reach Uranus in

five years (or less, in some cases). Of course, Neptune and Pluto still are unreachable without some special considerations.

2.2 ΔV MINIMIZATION

2.2.1 Introduction

The field of optimization is a powerful tool in the engineering design process. The basic optimization problem is one of determining the minimum or maximum a function, called the objective function, can obtain, subject to certain constraints on its variables. This problem is represented by

$$\min_{x \in R^n} f(x) \quad (2.2)$$

subject to the constraints

$$g_j(x) = 0 \text{ for } j = 1, \dots, m_e$$

$$g_j(x) > 0 \text{ for } j = m_e + 1, \dots, m$$

$$x_l < x < x_u.$$

The function $f(x)$ is the objective function and x is the design variable vector of length n , i.e. n design variables. There are m constraints, the first type being called equality constraints while the second type is called inequality constraints. The third type of constraint is on the design variables themselves and specifies the range of values that these variables can take. There has been much theory developed on techniques to solve optimization problems in the above form. The particular method selected depends upon the nature of the problem; the type of constraints, whether the problem is linear or non-linear, whether the gradients of the functions are to be evaluated analytically or by finite-difference methods, etc..

All of these factors will need to be considered when selecting the computer code to be used to solve the optimization problem.

With the above discussion in mind, an optimization problem studied this year will be discussed, namely the problem of ΔV minimization.

2.2.2 Background

One of the major problems that has surfaced in the first two years of development of Project WISH deals with the transfers from a nominal orbit to the planets in the solar system. It has been noted that the ΔV needed for these transfers have a great impact on the propulsion system requirements. As the values for the ΔV increase, the demands on the propulsion system become considerable. Besides straining the propulsion system, this has a cascade effect on the rest of the systems of the Emerald City; greater propulsion system requirements (thrusts, powered-flight times...) lead to more difficult problems in shielding, structural dynamics, propellant storage, etc... Thus, it is in the best interest of the Emerald City to keep these ΔV 's as low as possible. For this reason, it was felt that an optimization of ΔV was justified in order to keep propulsion system requirements as reasonable as possible. It may seem that this would be redundant with the work that was presented earlier in this chapter. However, the analysis presented there used a computer program that assumed an instantaneous change in velocity, with no regard for the powered-flight times, thrust required, or the thrust angles that could be used. By performing

this optimization, it is hoped that these factors can be taken into account, as well as determining the orientation between the Emerald City and the target orbit, typically near the destination planet, that will yield the lowest ΔV.

2.2.3 Assumptions

In order to carry out the optimization, certain assumptions regarding the nature of the orbits and transfers had to be made. The first assumption is that planets are all in circular orbits and are all in the ecliptic plane, i.e. the same plane as the Earth. As was shown in Table 2.1, this is a reasonable assumption for all of the planets except Mercury and Pluto, which are of the least interest in Project WISH. The second assumption made was that there is no loss of propellant during the free-flight phase of the transfer. Of course, there will be some boil-off of the liquid hydrogen due to heat leakage through the storage tanks, but for simplicity, it was ignored for this analysis. The validity of this assumption is questionable, but it was reasoned that the results would still be applicable for this preliminary study. By making this assumption, the acceleration at the end of the first powered-flight phase was set equal to the acceleration at the beginning of the second powered-flight phase.

The third, and most pivotal, assumption is that the trajectory during the powered-flight times is unaffected by the pull of the sun's gravity (see Figure 2.3). During the powered-flight times, the Emerald City is assumed to follow a projectile-like course,

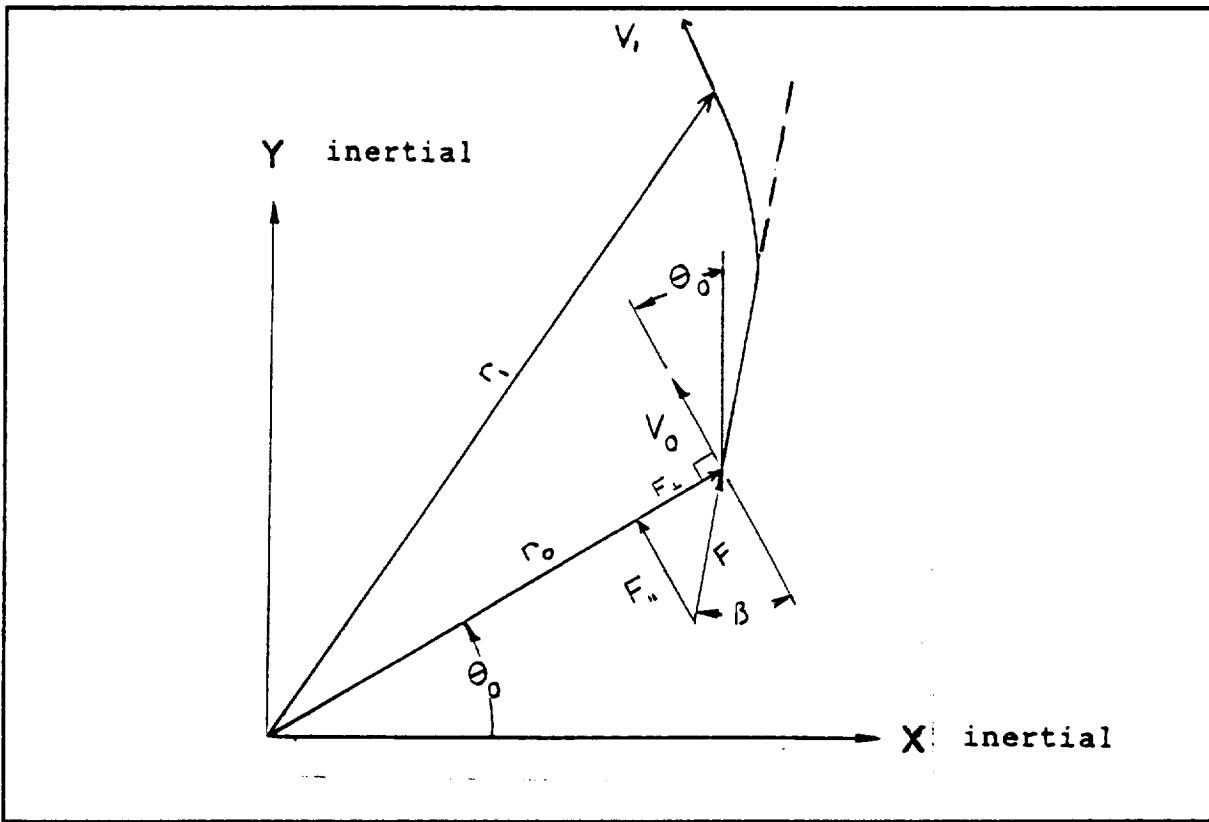


Figure 2.3 - Assumption for Powered-Flight Phases

determined by the X- and Y-components of the initial velocity and acceleration (thrust) vectors. This assumption is based on the value of the ratio of accelerations due to thrust and gravity during the powered-flight phases, given by

$$R(t) = \frac{a_{th}}{a_g} = \frac{F_{th}r(t)^2}{\mu m(t)} \quad (2.3)$$

$$m(t) = m_0 - mt \quad \mu = 1.327 \times 10^{11} \frac{\text{km}^3}{\text{s}^2}.$$

It can be seen that R is dependent upon the thrust, F_{th} , the radius, $r(t)$, and ship mass, $m(t)$. For representative values for the Emerald City, R will be a very large number, and thus it was felt that this assumption was valid for this preliminary investigation.

2.2.4 Geometry

The geometry that was used for the ΔV optimization is shown in Figure 2.4. The technique used to model the interplanetary transfer was to break down the transfer into three arcs. The first and last arcs represents the initial and terminal powered-flight phases, respectively, while the middle arc represents the free-flight phase. In the powered-flight portions, the thrust level, powered-flight times, and thrust angles govern the trajectory, while in the free-flight portion, the classical relationships governing orbiting bodies are used (more on these relationships can be found in Appendix A). The variables shown in Figure 2.4 are defined in Table 2.13.

Table 2.13 - Definition of Variables Used in
 ΔV Minimization Problem

r_0	- nominal orbit radius
r_1	- radius at end of first powered flight, beginning of free-flight
r_2	- radius at end of free-flight, beginning of second powered flight
r_f	- target orbit radius
θ_0	- angle between inertial reference frame X-axis and r_0 vector
θ_1	- angle between inertial reference frame X-axis and r_1 vector
θ_2	- angle between inertial reference frame X-axis and r_2 vector
θ_f	- angle between inertial reference frame X-axis and r_f vector
θ_i	- angle between inertial reference frame X-axis and target planet at launch
γ_0	- angle between inertial reference frame X-axis and eccentricity vector (line of apsides)
γ_1	- true anomaly of free-flight orbit at point 1
γ_2	- true anomaly of free-flight orbit at point 2

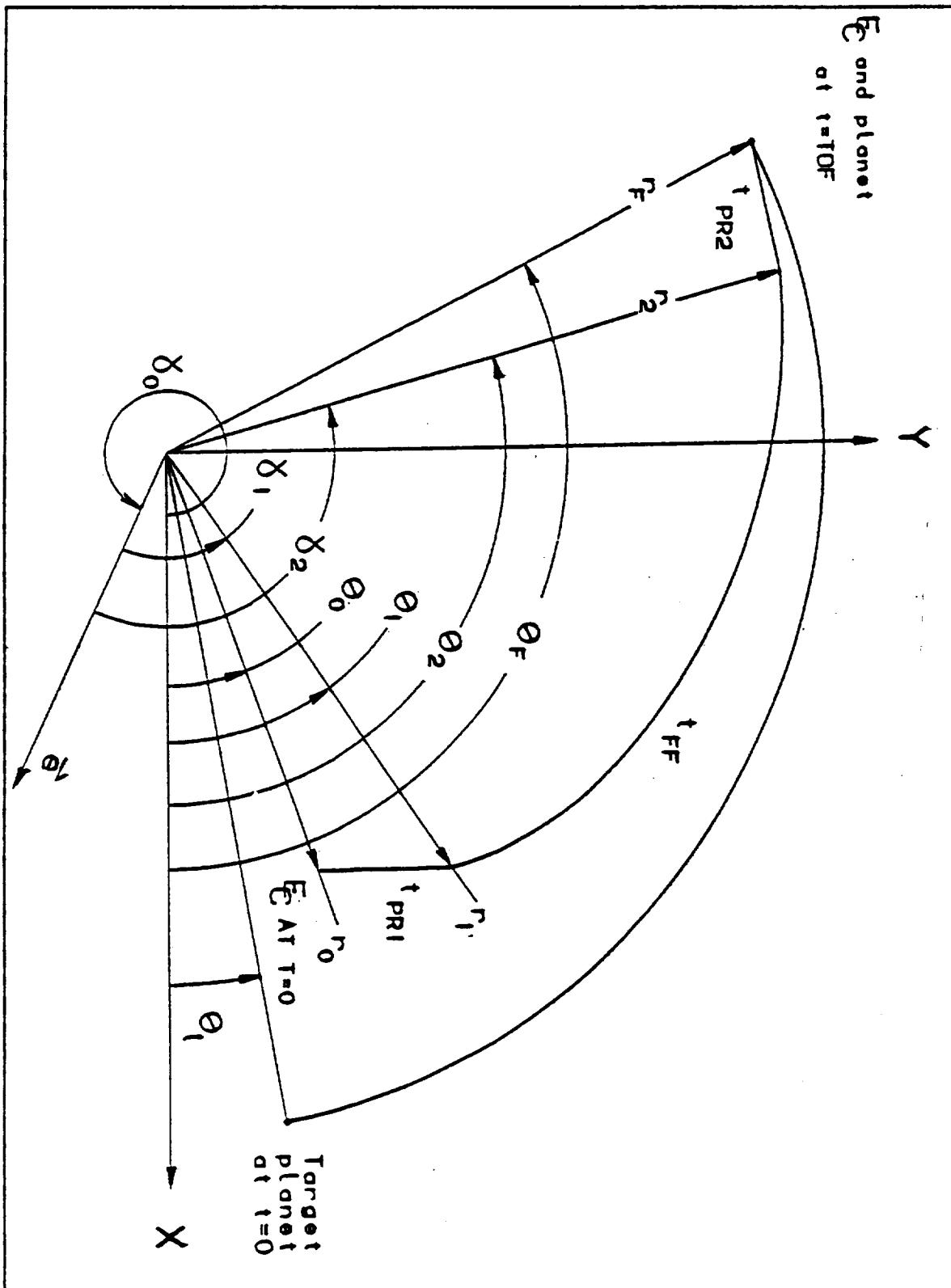


Figure 2.4 - Geometry for Optimization Problem

2.2.5 Methodology

In an optimization problem, there is a objective function that represents the variable to be optimized and constraint functions that represent the restrictions on the problem. For the ΔV minimization problem, the general objective function is

$$\Delta V_r = \Delta V_1 + \Delta V_2 - (\vec{V}_1 - \vec{V}_o) + (\vec{V}_f - \vec{V}_2) \quad (2.4)$$

where V_1 , V_o , V_f , and V_2 are the velocities at points 1, 0, f, and 2, respectively (see Figure 2.4). The general constraints for this problem are given by constraints on the total time-of-flight, the acceleration levels, the powered-flight time lengths, the rendezvous requirements, and physical variable constraints. The acceleration and powered-flight-time constraints arise from the limitations of the propulsion system, while the total time-of-flight constraint governs the allowable time to make the transfer. The rendezvous constraint requires that the position and velocity of the Emerald City at the end of the transfer matches the position and velocity of the target orbit near the destination planet at that time, and the final constraint is to ensure that there are no physically meaningless solutions found, such as negative times or negative magnitudes. Thus the problem is to find the equations that relate v_0 , v_1 , v_2 , and v_f to the design variables chosen and determine equations for the constraints listed above.

The first step that was taken was to define a state vector for point i, x_i , such that

$$\vec{x}_i = \{\vec{r}_i \quad \vec{v}_i\}. \quad (2.5)$$

The values at the end of each powered-flight phase can be related to the values at the beginning of each powered-flight phase by

$$\begin{aligned}\vec{x}_1 &= \vec{x}_o + \Delta\vec{x}_1 \\ \vec{x}_f &= \vec{x}_2 + \Delta\vec{x}_2\end{aligned}\quad (2.6)$$

where

$$\Delta\vec{x}_j = \{\Delta\vec{r}_j, \Delta\vec{v}_j\}. \quad (2.7)$$

By examining the equations governing the trajectory of the Emerald City during the powered and free-flight phases, and by contemplating the nature of the problem, eight design variables were identified. These variables are the two powered-flight times, t_{pr1} and t_{pr2} , the two thrust angles, β_1 and β_2 , the acceleration level, a_o , the true anomaly at the end of free-flight, γ_2 , and the initial orientations of the Emerald City and the target planet, Θ_o and Θ_i , respectively. The functional dependencies between these variables and the state vectors were found to be

$$\begin{aligned}\vec{x}_1 &= \vec{x}_o(\Theta_o) + \Delta\vec{x}_1(\Theta_o, a_o, t_{pr1}) \\ \vec{x}_f &= \vec{x}_2(\gamma_2)|_{\vec{x}_1} + \Delta\vec{x}_2(\gamma_2, a_o, t_{pr1}, t_{pr2})\end{aligned}\quad (2.8)$$

where the vertical bar signifies dependance on a previous state. After applying equations for ΔV_1 and ΔV_2 as found in Appendix A, the objective function was written as

$$\Delta V_T = -I_{sp}g[\ln(1 - \frac{a_o t_{pr1}}{I_{sp}g}) + \ln(1 - \frac{a_o t_{pr2}}{I_{sp}g - a_o t_{pr1}})], \quad (2.9)$$

where I_{sp} is the specific impulse of the propulsion system (see Chapter 3), and g is the gravity constant on the surface of the Earth, 9.81 m/s^2 . The constraint functions may then be written as

1. $t_{ff} + t_{pr1} + t_{pr2} < \text{TOF}_{\max}$
2. $a_0 < a_{0,\max}$
3. $t_{pr1} + t_{pr2} < t_{pr,\max}$
4. $x_{f,EC} = x_{f,T0}$.
5. $a_0, t_{pr1}, t_{pr2}, t_{ff} > 0$.

It turns out that the objective function is dependant only on three of the eight design variables, namely a_0 , t_{pr1} , and t_{pr2} . The other five design variables enter into the problem through the first and fourth constraints above. These constraints on the total time-of-flight and the rendezvous requirement incorporate the rest of the design variables through the equations governing the powered and free-flight phases of the trajectory. These equations can be found in detail in Appendix A.

Once the objective function and constraint functions are determined, an optimization code can be utilized to solve this problem. A potential optimization subroutine was identified, but due to time and personnel constraints, the problem was not programmed. This subroutine solves a general, non-linear optimization problem using a successive quadratic programming algorithm and finite difference gradients. It is hoped that this optimization problem can be programmed during next year's design effort and some meaningful results obtained.

2.3 CONCLUSIONS

This year, a detailed study was performed on the orbital mechanics of Project WISH. Based on this study, a nominal orbit of 4 AU's was selected, which places the Emerald City roughly 600,000,000 kilometers from the sun, between the orbits of Mars and Jupiter. From this orbit, it was determined that the planets Mercury, Venus, Earth, Mars, Jupiter, and Saturn can be reached 100% of the time in flight times of three years or less with a ΔV limit of 40 km/s one-way. Uranus can be reached 73% of the time with this ΔV in flight times of five years, which was felt to be adequate for this project. Neptune and Pluto cannot be reached at all at this ΔV with flight times of up to five years, but it was believed that there would be little need for a ship such as the Emerald City to make trips to these planets during the time frame considered. The ΔV minimization problem was also examined and equations were generated that yield the trajectory of the Emerald City during both the powered- and free-flight phases. The objective and constraint functions were determined, but due to a lack of time, the problem was not programmed into an optimization code. It is hoped that in the future, this problem can be solved and meaningful results can be obtained. Also, more work should be done on determining the ΔV 's required to return to the nominal orbit from a planet. With additional study in this area, a more accurate round-trip figure for the ΔV 's can hopefully be obtained. As of the end of this study, a total round-trip ΔV of 50 km/s was used as the upper ceiling for the Emerald City.

CHAPTER 3

PROPULSION

3.0 INTRODUCTION

The propulsion system of the Emerald City plays an important role in the success of Project WISH. For this reason, it was one of the most rigorously studied subsystems this year. At the conclusion of the Phase I design conducted last year, an antimatter engine was selected as the main propulsion system of the Emerald City². However, it was decided during Phase II that antimatter was too theoretical for the time frame of Project WISH, and that the propulsion system chosen should be more readily procurable by the mid-21st century. With the hope of bringing the choice of the propulsion system into the Emerald City's time frame, the propulsion team looked at several areas of interest in spacecraft propulsion. First, a general level study was conducted in order to determine some of the important parameters associated with spacecraft propulsion and what impact they had on the choice of a particular system. Once this was accomplished, a propulsion system was chosen and a specific propulsion study was conducted in order to determine the significant characteristics of this system. From this study, it was possible to calculate other important parameters that were dependent upon the choice of a particular propulsion system. Finally, this propulsion system was used in the design of two representative missions, which may be found in Chapter 6.

3.1 GENERAL PROPULSION STUDY

3.1.1 Theoretical Background

The purpose of this general level study is to determine which parameters play a major role in the choice of a propulsion system, and what the orders of magnitude of these parameters need to be for an application such as Project WISH. The study is independent of the type of engine that will be used for Project WISH; only the physical nature of spacecraft propulsion enters into this investigation. The first step in the analysis was to determine the effects that the mission requirements have on propulsion parameters. Since the Emerald City is expected to be a large spacecraft, the propulsion system will be required to produce high impulse levels, J , at high specific impulses, I_{sp} . High specific impulse, which is the impulse produced per unit weight of propellant expelled, is desirable because it corresponds to less propellant required to accomplish a mission. The I_{sp} plays an important role in the equation for the propellant mass ratio, given by

$$\frac{m_p}{m_o} = 1 - e^{-\frac{\Delta v}{I_{sp} g}} \quad (3.1)$$

which is plotted in Figure 3.1. This figure demonstrates how the propellant mass ratio, which is the fraction of the total initial ship mass consisting of propellant, decreases as the I_{sp} is increased or the Δv is decreased. Thus, to keep the propellant mass required for a given mission down, a propulsion system capable of generating a high I_{sp} should be utilized.

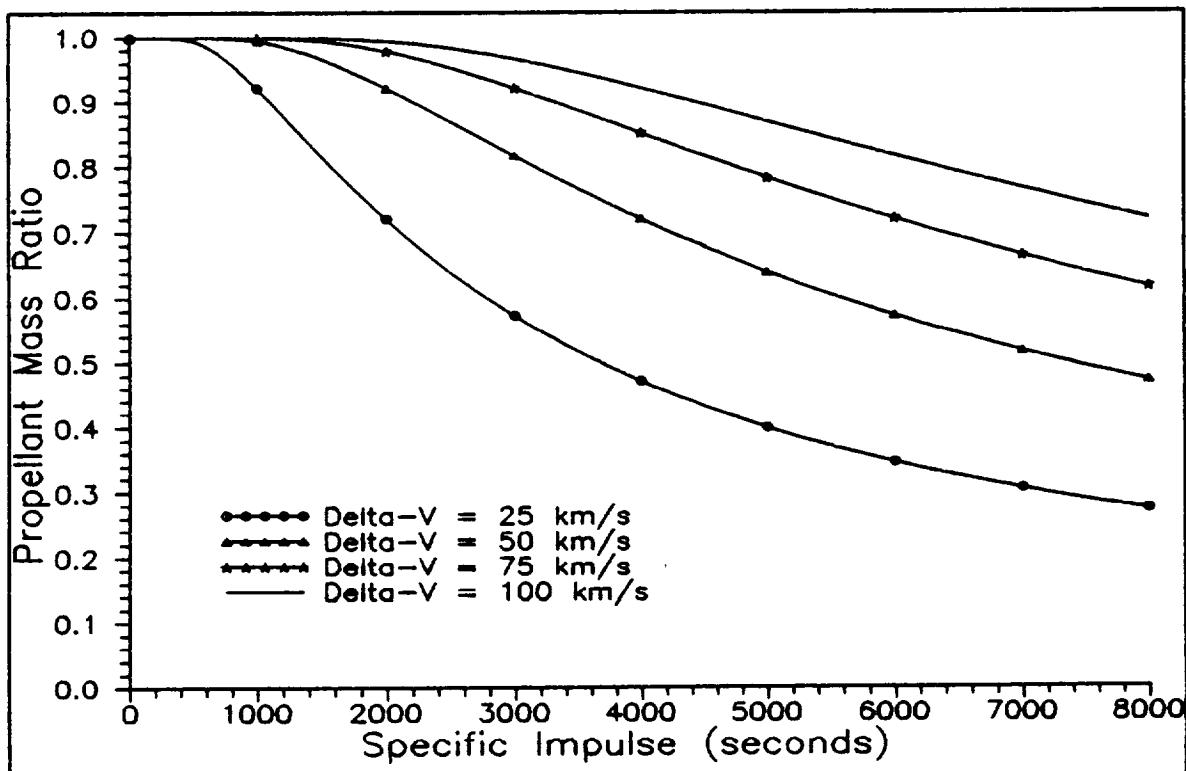


Figure 3.1 - Propellant Mass Ratio vs.
 I_{sp} With ΔV as a Parameter

However, for the Emerald City, a high- I_{sp} engine alone is not enough. An engine capable of producing high impulse levels as well as the high I_{sp} 's is needed. The impulse required for a mission is a function of the dry mass of the ship (no propellant included) and the ΔV and is given by

$$J = m_{dry} I_{sp} g (e^{\frac{\Delta V}{I_{sp} g}} - 1) \quad (3.2)$$

which is plotted in Figure 3.2. From this figure, it can be seen that the impulse required for an Emerald City mission will be very large, on the order of 10^{13} to 10^{14} newtons. This is due to two factors; the large dry mass of the Emerald City, and the high ΔV levels that will be required for its missions (see Chapter 2). The

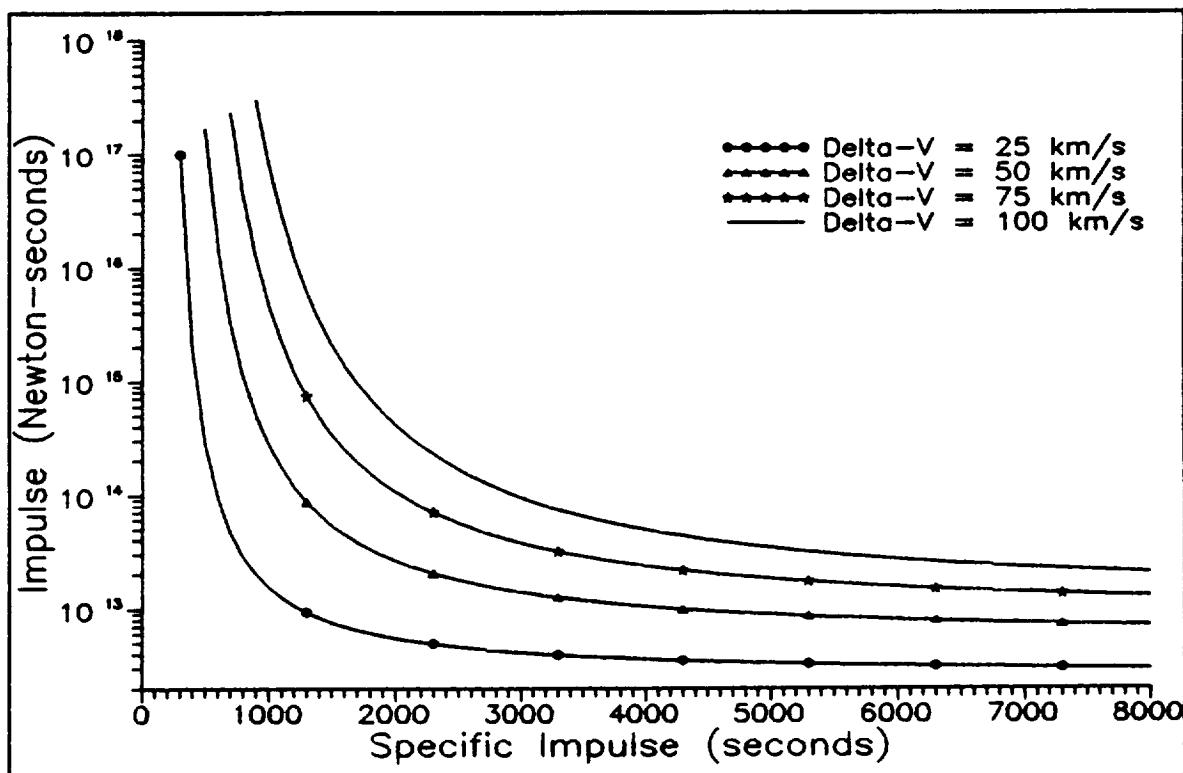


Figure 3.2 - Impulse vs. Specific Impulse with ΔV as a Parameter and $m_{dry} = 10^8 \text{ kg}$

effect that the I_{sp} has on the impulse required can also be seen from Figure 3.2. As the I_{sp} goes down, the impulse required goes up, eventually approaching infinity as I_{sp} approaches zero. This is because of the extra propellant mass that must be carried at the lower I_{sp} 's, which makes the Emerald City heavier and more difficult to move. Since impulse is the product of a force and a time, high impulses would necessitate high thrusts, F , and high powered-flight times, t_{pr} . Neither of these are desirable from an engine maintenance/lifetime viewpoint. It may also be seen from Figure 3.2 that, if the Emerald City were to burn for its entire flight time (~ 3 years or $\sim 10^8$ seconds), the thrust that would be required would still be on the order of 10^5 newtons.

Once it has been determined that high I_{sp} 's and high thrusts are needed, the next step was to search for a propulsion system that could satisfy these requirements. A general level study was conducted in an attempt to find such a system from choices that included chemical, electrical, nuclear, and antimatter. However, antimatter had already been ruled out for being too theoretical in nature, even for an advanced project such as Project WISH. Thus, the remaining systems were analyzed in terms of the specific impulse and thrust levels that each system could provide.

3.1.2 General Propulsion Systems

Chemical propulsion was the first type of propulsion analyzed and was promptly rejected. Although the thrust values were adequate, the specific impulses of these systems fell far short of the requirements that the Emerald City would place on them. Electrical propulsion was the next system that was studied. These systems produced high enough I_{sp} 's, but were severely limited in the amount of thrust that could be produced. Nuclear thermal propulsion (NTP) was the final type of system examined. Estimates of the nuclear propulsion systems of the 21st century gave the best combination of high thrust and high I_{sp} that would be required for Project WISH. Thus, NTP was examined in more detail as a primary propulsion system for the Emerald City.

One of the main points considered when examining nuclear systems was the question of fission or fusion. The propulsion group decided that fusion, like antimatter, would be too

theoretical for the Emerald City. Another drawback of using fusion propulsion is the mass penalty that would accompany the system. Compared to the fission systems, the fusion systems are estimated to be substantially more massive. Of course, a breakthrough in fusion research could lead to the development of an operational fusion system suitable for the Emerald City, but for now, fusion was rejected as a main propulsion candidate. Fission systems have the advantage of being more advanced and currently less massive than their fusion counterparts. Unfortunately, associated with fission is a rather troublesome radiation problem, which leads to an increase in the shielding mass required for human safety. Also, the more developed types of fission systems have relatively low I_{sp} 's for this project, and the more advanced engines with the higher I_{sp} 's are still conceptual in nature. With all of these considerations in mind, it was decided that a fission nuclear propulsion system would be used for the Phase II design of the Emerald City.

Within the fission category of NTP, there are two major subgroups; solid-core reactors and gas-core reactors. As its name suggests, a solid-core NTP system utilizes a fissioning solid-core of uranium to generate thermal energy. This energy is transferred to a lightweight propellant, usually hydrogen, which is then expelled through a convergent-divergent nozzle. However, the core is limited in temperature by material considerations, and thus the achievable I_{sp} is similarly limited. Current estimates and some testing during the NERVA (Nuclear Energy Rocket Vehicle Appli-

cation) place the solid-core I_{sp} in the range of 800-1100 seconds⁵. The gas-core NTP system attempts to overcome this issue of limited temperature by allowing the core temperature to increase beyond the boiling point of uranium, thus resulting in a gaseous core. This increase in temperature enables more thermal energy to be transmitted to the propellant, which results in a higher possible I_{sp} . Current theoretical studies give a possible I_{sp} for this conceptual engine on the order of 2000-8000 seconds⁶. It was felt that the I_{sp} of the solid-core rockets were simply too low for the needs of Project WISH (see Figures 3.1 and 3.2) and thus the gas-core NTP system, with its higher estimated attainable thrusts and I_{sp} 's was chosen for further study as the main propulsion system of the Emerald City.

There were two major types of gas-core nuclear rockets (GCNR) studied, the light bulb (closed-cycle, LBGCR) and space radiator (open-cycle, SRGCNR). The closed-cycle gas-core engine has its gaseous core encased in a transparent material that allows radiation from the fissioning core to heat the propellant while keeping the propellant and core physically apart. The open-cycle gas-core engine has the propellant and core in direct contact, which allows for better heat transfer, but also leads to a loss of uranium from the core. In determining which of these propulsion systems was best for the Emerald City, three main engine parameters were investigated, the I_{sp} , the thrust per engine, F_i , and the mass per engine, m_{vi} . Table 3.1 shows some comparison figures of these three parameters for the two systems considered⁶. This table shows that

the closed-cycle engine has a significantly lower specific impulse than the open-cycle engine. However, the maximum expected thrust value for the closed-cycle system is higher than that of the open-cycle engine. It will be shown later in this chapter in Figure 3.5 that the advantage of producing higher thrust decreases as the thrust level increases. It was felt that the closed-cycle gas-core engines still had I_{sp} values that were too low for use by the Emerald City, and

thus, the open-cycle engine (hereafter referred to as SRGCNR) was chosen as the propulsion system for the Emerald City. The values of thrust and I_{sp} that were used as representative figures for the SRGCNR in the remainder of this report are⁷

$$I_{sp} = 5000 \text{ seconds}$$

$$F_i = 4.4 \times 10^5 \text{ N.}$$

These values fell within the range of thrusts and I_{sp} 's that were discussed in Reference 7, and were felt to be reasonably obtainable if the SRGCNR is ever developed. Once the propulsion system and important parameters were determined, it was then possible to conduct a detailed study of the SRGCNR system of the Emerald City.

Table 3.1 - Comparison of I_{sp} , F , and m_i for LBGCR and SRGCNR

LBGCNR DATA		
Thrust (N)	m_i (kg)	I_{sp} (sec)
133,370	14,050	1780
1,334,200	34,475	2355
4,002,800	385,500	2635

SRGCNR DATA		
Thrust (N)	m_i (kg)	I_{sp} (sec)
22,240	36,280	2400
177,900	101,440	5500
444,750	213,350	6000

3.2 SPACE RADIATED GAS-CORE NUCLEAR ROCKET STUDY

With the specific propulsion system determined and values for I_{sp} and F_i known, it was then possible to perform a more detailed study of this system. Because the SRCGNR is so conceptual in nature, there are many unanswered questions about its form and function. Figure 3.3 is a schematic of the GCNR that was conceptually developed at NASA Lewis Research Center by Mr. Robert Ragsdale⁷. The main mechanical components of this engine are the pressure shell, the moderator, the turbopump, the nozzle, and the

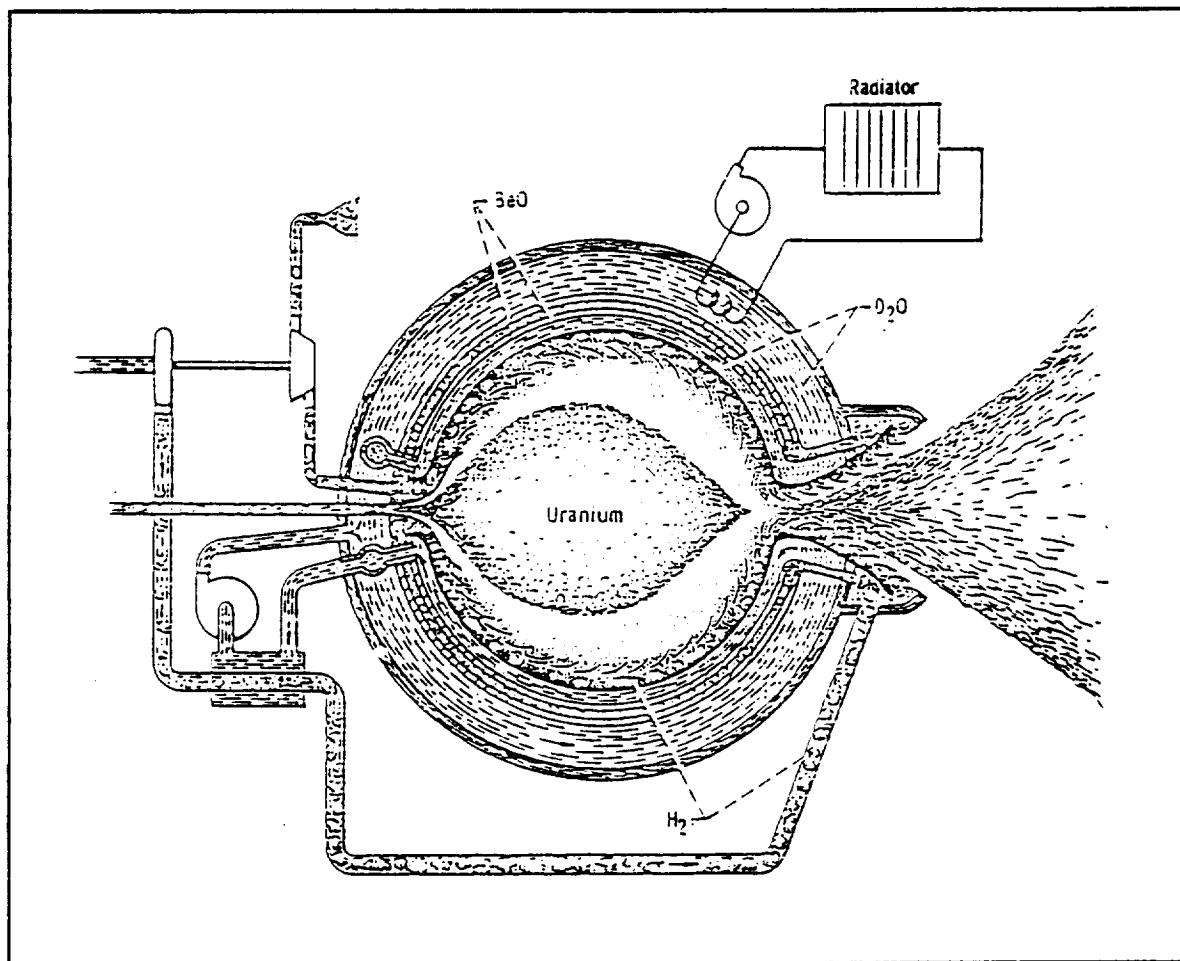


Figure 3.3 - Conceptual Sketch of the Gas-Core Nuclear Rocket

radiator, which work together in the following manner. First, liquid hydrogen is pumped through the moderator by the turbopump to aid in heat removal there. Then, the hydrogen is pumped into the cavity where the uranium isotope, U^{233} , is undergoing the fission process. The hydrogen absorbs heat from the fissioning uranium and is expelled through the nozzle to produce thrust. The moderator is used to reflect and reduce the energy of (thermalize) the neutrons which aids in sustaining the fission process. The pressure shell encloses the core, cavity, and moderator, while the radiator is used to remove any excess heat that builds up in the engine which cannot be removed by the hydrogen alone.

Once a working knowledge of the engine had been acquired, it was then possible to compute various important engine characteristics. These computations were done using a computer program written during this study, which can be found listed in Appendix B. This program was used to generate the important parameters of the SRCGNR from general equations and equations given by Mr. Ragsdale for estimating the mass of an engine⁷. The results obtained from this program may be found tabulated in Table 3.2. The program has four inputs that need to be determined before the other parameters may be calculated. These inputs are I_{sp} , F_i , cavity diameter, D_c , and the ratio of the volume of the gaseous uranium core to the volume of the cavity, V_u/V_c . For the data in Table 3.2, these values were selected to be $I_{sp} = 5000$ seconds, $F_i = 4.4 \times 10^5$ newtons, $D_c = 3.3$ meters, and $V_u/V_c = 0.23$. These figures were considered to be reasonable estimates of the operating conditions

**Table 3.2 - Engine Parameters of a SRGCNR, $F_i = 4.4 \times 10^5$ N,
 $I_{sp} = 5000$ s, $D_c = 3.3$ m, and $V_u/V_c = 0.23$**

SPECIFIED VALUES:

$I_{sp}=5000.00$ s Thrust=440000.00 N $V_u/V_c=.23$ $D_c=3.30$ m

CALCULATED ENGINE PARAMETERS:

ENGINE CAVITY CONDITIONS:

$T(H_2)=25165.49$ K	$T(U^{233})=76183.45$ K
Cavity Pressure=981.25 atm	Critical Mass $U^{233}=40.12$ Kg
Cavity Volume=18.82 m ³	Uranium Volume=4.33 m ³
Uranium Diameter=2.02 m	Uranium Density=9.27 Kg/m ³
Hydrogen Molecular Mass=0.759	Gamma=1.261

MASS FLOW RATES:

H_2 -To- U^{233} Ratio=393.89	Propellant=8.97 kg/s
$H_2=8.951$ kg/s	$U^{233}=0.023$ kg/s

ENGINE DIMENSIONS:

Pressure Shell Thickness=0.087 m	
Pressure Shell Mass=52597 kg	
Moderator Thickness=0.76 m	Moderator Mass=46632 kg
Turbo Pump Mass=773 kg	Exhaust Nozzle Mass=233 kg
Radiator Mass=138463 kg	Total Engine Mass=238682 kg

VARIOUS ENGINE PARAMETERS:

Reactor Power=16185.08 MW	Radiated Power=971.10 MW
Specific Mass=0.02224 kg/KW	Jet Power=10787.32 MW
Thrust to Weight Ratio=0.188	Engine Efficiency=0.6665

THROAT CONDITIONS:

Temperature=22258.87 K	Pressure=524.48 atm
Hydrogen Molecular Mass=0.843	Gamma=1.246
Area=0.0022 m ²	Velocity= 16542.23 m/s

EXIT CONDITIONS:

Temperature=4120.51 K	Pressure=0.115 atm
Hydrogen Molecular Mass=2.004	Gamma=1.226
Area=0.6489 m ²	Velocity= 49033.25 m/s
Exit-To-Throat Area Ratio=300	Mach Number= 6.50

of the SRGCNR engine⁷. With these inputs, the program was able to calculate the conditions in the cavity, in the throat, and at the exit of the engine. The formulas that were used to calculate these conditions are included with the program in Appendix B. Some of the more interesting results noted from Table 3.2 are a throat temperature of 22,260 K, a jet power of 10.8 gigawatts, a reactor power of 16.1 gigawatts, a thrust-to-weight ratio of 0.19, and an exit velocity of 49 km/s. This value of exit velocity is over ten times what a standard chemical rocket can attain today. The overall mass of the engine was found to be 238.7 metric tonnes.

Once the SRCGNR characteristics and values were obtained, it was then possible to proceed with other calculations that were related to the propulsion system. For example, the total number of engines, n , that would be required for any given mission had to be determined. This formula, given by

$$n = \frac{m_{dry} I_{sp} g}{F_i t_{pr}} (e^{\frac{\Delta v}{I_{sp} g}} - 1) \quad (3.3)$$

was found by replacing J in Equation 3.2 with $n F_i t_{pr}$. Once the number of engines was determined, it was possible to calculate the total engine mass from

$$m_w = n m_{wi}. \quad (3.4)$$

Equation 3.3 is plotted in Figure 3.4, which shows the relationship between the number of engines required and the mission ΔV for a range of different powered-flight times. This figure was generated using an I_{sp} of 5000 seconds, an F_i of 4.4×10^5 newtons,

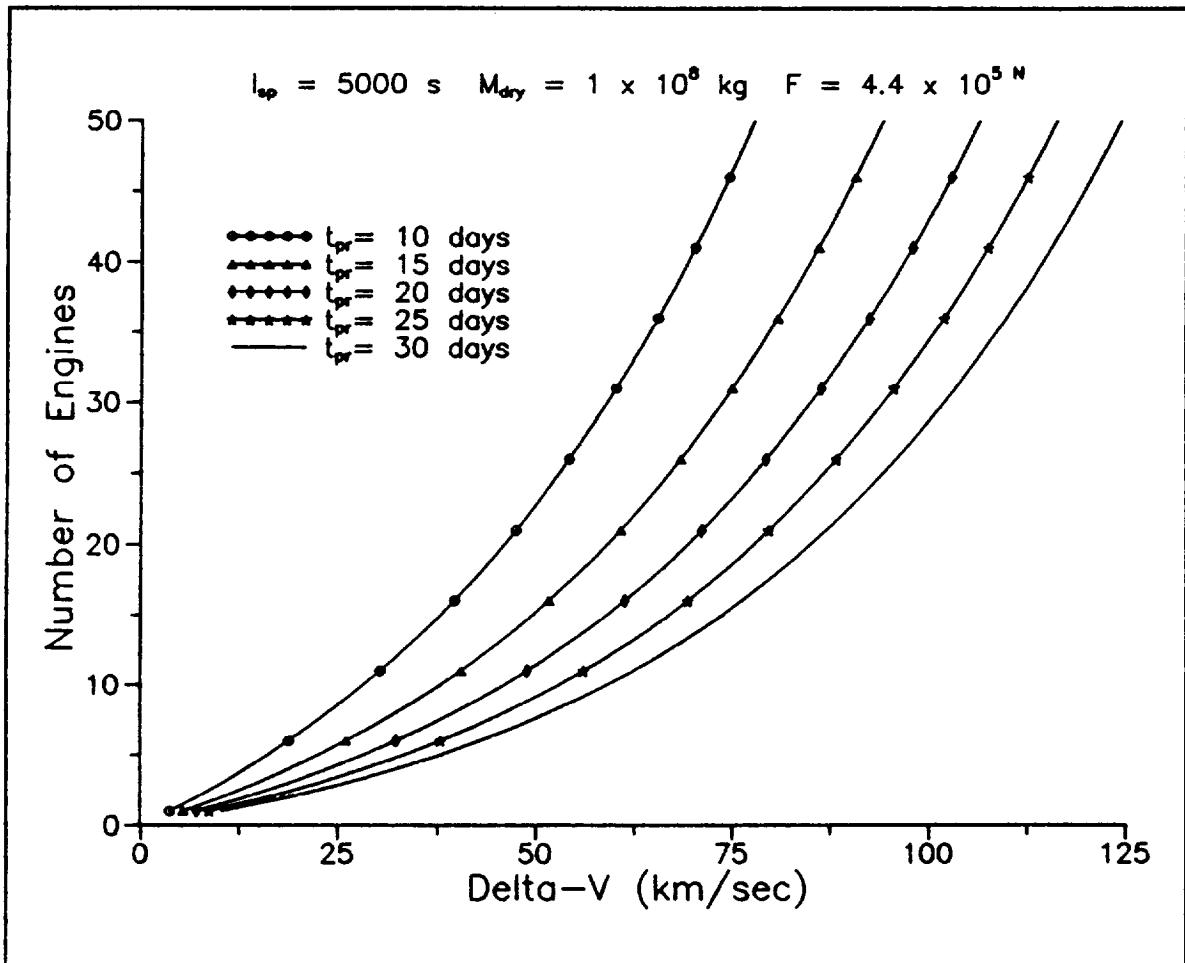


Figure 3.4 - Number of Engines vs. ΔV with Powered-Flight Time a Parameter

and an assumed dry mass of $1 \times 10^8 \text{ kg}$. By using Equation 3.3, the number of engines for any selected mission parameters (ΔV , t_{pr} , m_{dry}) may be determined. Once the total engine mass has been found, it was then possible to calculate the payload mass in the form of the payload mass ratio, given by

$$\frac{m_L}{m_o} = e^{-\frac{\Delta V}{I_{sp}G}} - \frac{I_{sp}G}{I_{spe}} (1 - e^{-\frac{\Delta V}{I_{sp}G}}). \quad (3.5)$$

In Equation 3.5, I_{spe} is defined as the engine specific impulse and is defined as the impulse produced per unit mass of the engine, or

$$I_{spe} = \frac{F_i t_{pr}}{m_{wi}} \quad (3.6)$$

Equation 3.5 was used to generate Figure 3.5, which graphically shows the relationship between the payload mass ratio and the engine specific impulse I_{spe} for different mission ΔV 's. An interesting note about this plot is that the payload mass ratio

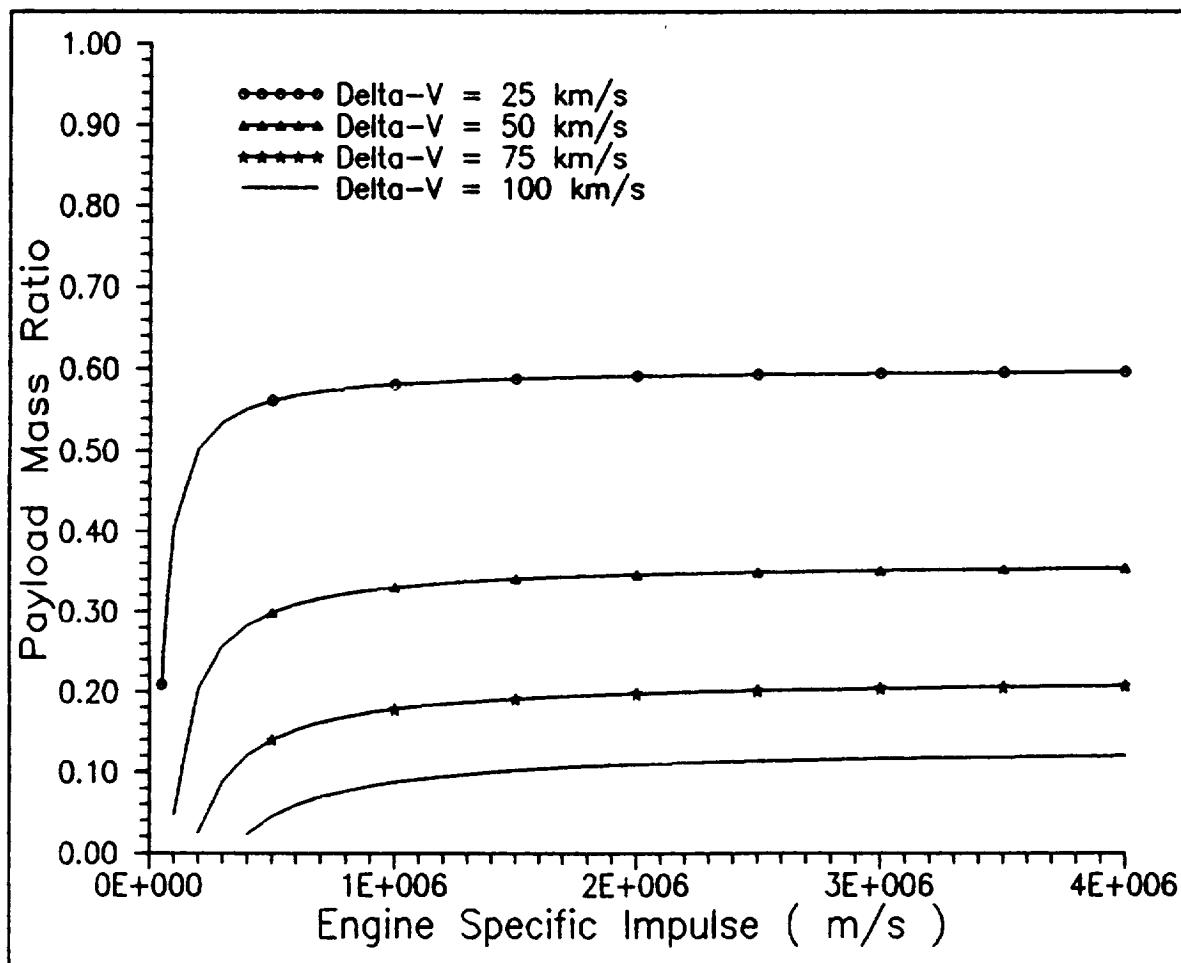


Figure 3.5 - Payload Mass Ratio vs. Engine Specific Impulse (I_{spe}) with ΔV as a Parameter.

tends to level out no matter how much the engine specific impulse is increased. Thus, an increase in the I_{sp} is only beneficial when operating in the region where the payload mass ratio substantially increases. There is little to be gained by increasing the thrust or the powered-flight time or decreasing the engine mass once the I_{sp} has reached the point where the payload mass ratio begins to level off. Also, it may be noted from Equation 3.5 that there is a value of I_{sp} below which, the engine mass exceeds the entire payload mass, and thus the payload mass ratio will be negative.

3.3 CONCLUSIONS

The end result of the analysis presented in this chapter was to find equations that would yield the total mass of the propulsion system and propellant required. By using the equations and figures given here, these masses can be found for different mission specifications. This is a crucial step in the design of the Emerald City for specific missions. Two missions were designed for the Emerald City, using the equations derived here. These missions can be found in Chapter 6.

The preliminary propulsion system that was chosen was the space radiated open-cycle gas-core nuclear rocket engine. The benefits of this system are its high I_{sp} and thrust values that can be obtained. However, this engine is still very conceptual in nature, and so it is not currently known if the idea will eventually lead to a functioning rocket engine or not. It can be seen from Table 3.2 that the temperature in the throat of the

nozzle is predicted to be around 22,000 K!. Clearly, advances will have to be made in the development of materials capable of withstanding this kind of thermal load. Another area in need of development is the confinement of the gaseous core. Currently, it is envisioned that the core will be confined by a vortex of inert gas. This area will need to be thoroughly researched if the concept of an open-cycle gas-core reactor is ever to reach fruition.

There were two detrimental side effects noted by using the open-cycle engine, both of which are related. The first of these effects was the loss of uranium out of the cavity and through the nozzle. It was estimated that approximately 2 metric tonnes of uranium will be lost per engine per day of powered-flight time. The second side effect is the environmental and human factors concern of the radiation generated by this type of engine. Large amounts of radiative material are present in the exhaust plume which will result in massive shielding requirements for the crew. Both of these problems can be lessened by going to a light-bulb gas-core engine, which is a closed-cycle type of engine. However, this engine is not foreseen to have an I_{sp} as high as that of the open cycle engine. The light bulb engine could prove useful if the scope of Project WISH were to ever be reduced, i.e. fewer people, less massive ship, smaller ΔV 's... Until then, however, the open cycle gas-core engine will remain as the only type of nuclear engine capable of generating the high impulse-high I_{sp} combination needed for Project WISH in the mid-21st century.

CHAPTER 4

ATTITUDE CONTROL

4.0 INTRODUCTION

Attitude control is an important facet of Project WISH due to the fact that it will be necessary to damp out oscillations in attitude due to disturbances. Because the Emerald City will be spinning to produce artificial gravity (see Chapter 5), the system will be gyroscopic in nature. Therefore, stable equilibrium configurations had to be determined, which was done during the Phase I study conducted last year. Once these configurations were known, attitude control studies were conducted in order to find the control requirements needed to return the Emerald City to equilibrium following a disturbance. The methodologies used to perform these attitude control studies are the focus of this chapter.

4.1 ATTITUDE DYNAMICS BACKGROUND

For a body that is as large and complex as the Emerald City, there will be some structural deformations that arise due to the loads encountered. However, for the purpose of this preliminary investigation, the Emerald City was considered to be a rigid body, i.e. there are no deformations present. Although structural dynamics was not considered in this analysis, it was examined last year using a lumped-mass modelling method, and will again be considered in detail during the third year (1991-1992) of the

project. Since the goal of the attitude control study was to obtain an order of magnitude estimation of the control thruster requirements, it was felt that the rigid body assumption was adequate.

As stated earlier, the stable equilibrium configurations for the Emerald City were determined from last year's vehicle dynamics study². These stable configurations were found to be dependent on the parameters b and r in the following manner:

1. $b > 1/r$ and $b > 4/r - 3$
2. $b < 1/r$ and $r > 1$
3. $b < 4/r - 3$ and $r < 1$.

The parameters b and r are given by

$$r = I_z / I_x = \text{slenderness ratio}$$

$$b = n / \Omega = \text{spin rate} / \text{orbital angular rate}$$

where I_z and I_x are the mass moments of inertia about the z- and x-axes (see schematic in Chapter 6), and n is the spin rate of the torus. Thus, it may be seen that the stability of the Emerald City depends upon three principal factors: mass moments of inertia (determined by ship configuration), spin rate (determined from artificial gravity considerations), and orbital angular velocity (determined by the nominal orbit).

4.2 CONTROL SYSTEM REQUIREMENTS

Once the stable configurations of the Emerald City are known, the control aspect of the problem may be examined. The main goal

of the attitude control study was to determine the values of thrust, root-mean-square power, and propellant mass required to damp out an initial disturbance.

4.2.1 State Feedback Control Design

The first step in achieving this goal was to determine the state-space equations that model the motion of the Emerald City. This equation was expressed in the non-dimensional state-space formulation⁸

$$\hat{\dot{x}} = [A][\hat{x}] + [B][\hat{T}] \quad (4.1)$$

where

$$[A] = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ (1-r) & 0 & 0 & (2-r) \\ 0 & (1-r) & (r-2) & 0 \end{bmatrix}$$

$$[B] = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (4.2)$$

$$[\hat{x}] = [\hat{\theta}_1 \ \hat{\theta}_2 \ \hat{\dot{\theta}}_1 \ \hat{\dot{\theta}}_2]$$

and $[\hat{T}]$ is the non-dimensional torque provided by the control thrusters ($\hat{\cdot}$ denotes non-dimensionalized quantities). Equation 4.1 is used to simulate the state response of the Emerald City for given ship configurations, thrust input configurations, and initial disturbances. A linear quadratic regulator control program (MATLAB⁹ software) was used to obtain the non-dimensional state

response that minimizes the control design performance index, defined by

$$CDPI = \frac{1}{2} \int_0^T (\hat{x}^T \hat{x} + \hat{f}^T \hat{f}) d\tau. \quad (4.3)$$

By minimizing this performance index, the program minimizes the total control effort and the kinetic energy of the system and yields a linear state feedback control law

$$[\hat{T}] = [G][\hat{x}] \quad (4.4)$$

where G is the control feedback gain matrix minimizing the CDPI in Equation 4.3.

4.2.2 Attitude Control Power Required

For the control torques of Equation 4.4, the non-dimensional control power consumed can be found by the non-dimensional power S^* ,

$$S^* = \int_0^T \hat{f}^T \hat{\theta}^{-T} \hat{\theta}^{-1} \hat{f} d\tau \quad (4.5)$$

which yields

$$S^* = \hat{x}_o^T P^* \hat{x}_o \quad (4.6)$$

for any initial disturbance state \hat{x}_o . The power matrix P^* is the solution of the linear matrix equation

$$A_{cl}^T P^* + P^* A_{cl} + G \hat{\theta}^{-T} \hat{\theta}^{-1} G = 0 \quad (4.7)$$

where

$$A_{cl} = A + BG \quad (4.8)$$

and the non-dimensional thruster distribution matrix is defined by

$$\hat{D} = D_t^{-1} [D] \quad (4.9)$$

in which D_t is the torus diameter and the elements of $[D]$ are the moment arms of respective input forces yielding moments about the centroidal body axes x and y of the vehicle which are parallel to the torus plane. The required quantities and matrixies in Equations 4.4 through 4.9 can be evaluated by using any suitable control software such as the MATLAB Control Toolbox mentioned previously.

The various dimensional and non-dimensional quantities are related by

$$[\theta_1 \ \theta_2 \ \dot{\theta}_1 \ \dot{\theta}_2] = [\hat{\theta}_1 \ \hat{\theta}_2 \ \hat{\dot{\theta}}_1 \ \hat{\dot{\theta}}_2] \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & n & 0 \\ 0 & 0 & 0 & n \end{bmatrix} \quad (4.10)$$

$$t_{con} = \frac{\tau_c}{n} \quad (4.11)$$

$$F_i = \hat{F}_i \frac{I_z n^2}{D_t}. \quad (4.12)$$

$$T = \hat{F} I_z n^2. \quad (4.13)$$

The non-dimensional control thrust forces can be obtained via

$$\hat{F}_{con} = D^{-1}\hat{f} \quad (4.14)$$

In all of the above equations, a ^ above a variable denotes non-dimensional quantities. The root-mean-square power required to damp out a disturbance can then be found from the value of S^* , computed via Equations 4.6 and 4.7. The root-mean-square control power required is then given by the formula

$$P_{rms} = \frac{v_{ex} I_s n^2}{2D_t} \sqrt{\frac{S^*}{\tau_c}} \quad (4.15)$$

where v_{ex} is the exit velocity of the control thrusters.

4.2.3 Attitude Control Propellant Requirement

The propellant mass required for the control thrusters can be found by the formula

$$m_{p,con} = \left(\frac{I_s n}{D_t v_{ex}} \right) \sum_{j=1}^f \int_0^{\tau_c} |\hat{F}_j| d\tau \quad (4.16)$$

where f is the total number of inputs used. The integral in Equation 4.16 is found by numerically integrating the non-dimensional thrust input versus non-dimensional time plots (see for example Figure 6.4 for specific mission designs)

4.2.4 Attitude Control Thruster Configuration

For a body with the size of the Emerald City, one would need hundreds, perhaps thousands, of control thrusters to exert attitude control torques about the body axes. The number would depend on

the thrust output capabilities of the control thrusters. Taking into account so many thrusters individually in the attitude control problem study would result in a very large D (thruster distribution) matrix. However, because the Emerald City is assumed rigid, one can instead consider only a few clusters of thrusters, where each cluster is represented as if it is a single thrust force obtained as the resultant force of hundreds of thrusters each producing identical thrust-time histories in a given cluster location. Thus, each cluster location acts as one input in the control study. After finding the total thrust-time history at a particular location through the control study, one can then apportion equally the required thrust to individual thrusters. Thus, for given thrust capabilities of thrusters, the total number of thrusters required in a particular cluster can be found subsequently. For example, in Figure 6.5, only three cluster locations are shown as if there are only three control thrust inputs, F_1 , F_2 , and F_3 , and the attitude control requirements are computed for that particular input configuration. How many individual thrusters may exist at each cluster becomes immaterial at this point and the control study can proceed.

4.3 ATTITUDE CONTROL DESIGN METHODOLOGY

The methodology developed in this chapter can be used to study the attitude control of the Emerald City for a wide range of ship configurations, thruster configurations, and initial disturbances. Two particular scenarios were examined and the control system

requirements were determined using the methods provided above. The results for particular mission studies can be found in Chapter 6. The outline of the methodology as described above is reviewed here in step-by-step form.

1. Choose a cluster configuration, characterized by Equation 4.9, to be studied and determine the slenderness ratio, r , from the ship configuration. Select an initial mean disturbance to investigate.
2. Use MATLAB (or a similar linear quadratic control regulator program) to determine the feedback gain, G , and the state response, x , to Equation 4.1 that minimizes the control design performance measure of Equation 4.3.
3. Use MATLAB to find the control torque, T , and the resultant cluster inputs, F (via Equation 4.14), versus time profiles, the non-dimensional power parameter, S^* , and observe the non-dimensional control time, τ_c , from the x response plots.
4. The resultant cluster thrusts required, F_i , for the control system can be found from F and dimensionalizing according to Equation 4.12. The root-mean square power and propellant required can be found from Equations 4.15 and 4.16, respectively.

One of the more important results obtained from the attitude control study was that the root-mean-square power required to damp out a disturbance is proportional to the square of the spin rate,

as shown in Equation 4.15. However, the torus diameter, D_t , can be written in terms of the spin rate and the g-level to be provided (see Chapter 5) as

$$D_t = \frac{n_g g}{2n_s^2} \left(\frac{60}{2\pi} \right)^2 \quad (4.17)$$

where the spin rate n_s is now in revolutions per minute (rpm's). Inserting this equation into Equation 4.7 and converting the spin rate to rpm's yields

$$P_{rms} = \left(\frac{2\pi}{60} \right)^4 \frac{v_{ex} I_x n_s^4}{n_g g} \sqrt{\frac{S^*}{\tau_c}}. \quad (4.18)$$

Equation 4.18 clearly shows the benefit of keeping the spin rate below 1 rpm (since for $n < 1$, $n^4 < n$) in order to decrease the power requirements for attitude control. This result was taken into account in human factors studies when the torus was designed (see Chapter 5).

4.4 CONCLUSION

This year, the work on the dynamics and control aspect of Project WISH focused on determining the attitude control system requirements. A methodology was established to perform attitude control studies for a wide variety of missions. This methodology, which is summarized above, was used to design the attitude control system for the two missions of the Emerald City. The results of these mission designs can be found in Chapter 6.

CHAPTER 5

HUMAN FACTORS

5.0 INTRODUCTION

Maintaining a habitable environment in space presents problems with varying degrees of difficulty depending upon its size and how long that environment is to be maintained. Something such as food supply, which is a relatively minor concern on a shuttle mission, becomes a problem that could dominate the design of a spacecraft with a crew of between 500 and 1000 and an operational lifetime of fifty years. Because of the magnitude of the Emerald City, human factors will play an important role in its design. This chapter covers three topics that relate directly to the design of the spacecraft: the life support system, the need for artificial gravity, and the problem of radiation.

5.1 LIFE SUPPORT SYSTEM

Last year, the different functions of life support were approached using mechanical systems². Separate systems were used for air revitalization, temperature and humidity control, waste management, and so forth. However, there are two major faults with using mechanical systems. Because of the three year plus mission times expected for Emerald City, all of these systems would have to run (unrealistically) with one-hundred percent efficiency. This is necessary to prevent compounds such as air or water from being recombined into products that cannot be recycled. More importantly

though, is that since these systems are mechanical, they are subject to breakdown and will eventually need spare parts. Storing these parts or making provisions for their manufacture would waste valuable space and add extra mass to the ship. For these reasons, another concept was explored for the primary life support system: biospheres.

A biosphere is a totally enclosed ecological system, with energy as its only input. The collective biomass of the earth is referred to as Biosphere I. Since all air, water, and waste is recycled internally, life can be sustained indefinitely. Clair Folsome created the first human-made biosphere inside a lab flask¹⁰. The flask contains only simple organisms, but it has been alive since it was sealed in 1968. What is proposed for Project WISH is that a scaled and more efficient version of Biosphere I be used as the primary life support system. Research is already being done to create biospheres large enough for human occupation. The Biosphere II project¹⁰ in Oracle, Arizona has constructed an environmental facility sealed off from the atmosphere that uses its land and water four and ten times as efficiently as Biosphere I¹¹. Total recycling of all atmospheric carbon dioxide takes place in half a day instead of eight years. The 150,000 cubic meter facility is designed as an environment for eight people who were recently sealed inside for a two year study. This figures to roughly 19,000 cubic meters per person. Even though this number would probably shrink if research were devoted to reducing the volume needed per person, it was used for sizing the crew section

to allow extra space for manufacturing, food processing, or other needs that have not yet been considered. The equation for the volume required in the torus section was then given by

$$V_{\text{torus}} = 19000N \quad (5.1)$$

where N is the number of crew members on the Emerald City. Research is currently aimed at understanding more about Biosphere I and to possibly extend man made biospheres onto other planets. It was believed that the concept of biospheres could legitimately be considered for a spacecraft with the life expectancy and magnitude of Project WISH.

5.2 ARTIFICIAL GRAVITY AND SHIP DESIGN

Of the little information known about long term effects of zero-g on the body, none of it is very positive. Without gravity, bones decalcify and muscles weaken and atrophy. A condition that could be described as "space anemia" also occurs¹². This is due to a drop in the production of red blood cells. This otherwise harmless condition could pose a serious health problem if an astronaut were injured or became ill. To counter these effects, the crew section of Emerald City was designed as a torus rotating about a central hub to provide some level of artificial gravity. Even though providing 1 g would eliminate these effects, considerable power and mass savings can be made if an acceptable lower g-limit can be found. The relationship between rotation rate, distance from the spinning axis, and g-level is shown in Figure 5.1. Since the volume requirement (from Section 5.1) and shape for

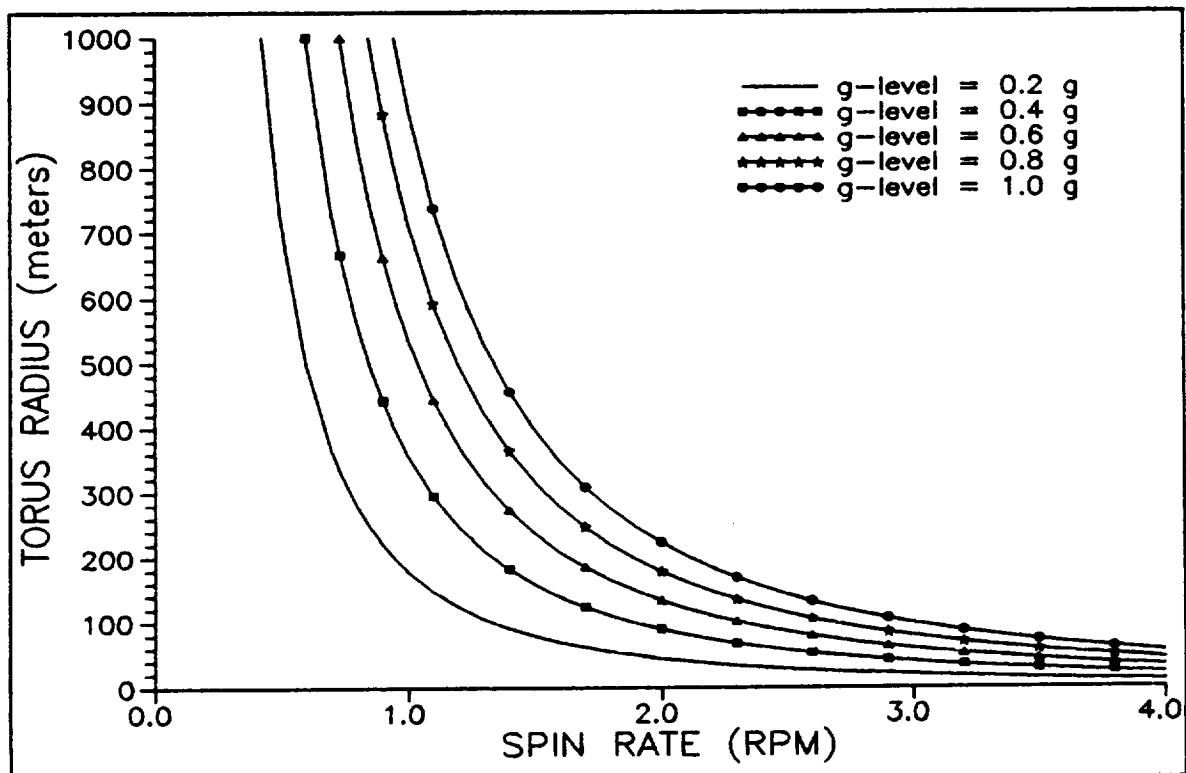


Figure 5.1 - Radius vs. Spin Rate for Different Gravity Levels

the crew section is known, the actual geometry is determined from the g-level and spin rate desired. Several possible geometries are listed in Table 5.1. Selection of the major radius of the torus, R (see Figure 6.1), is dependant on the constraints set for g-level and spin rate. One revolution per minute is used as an upper limit on spin rate because the power needed to maintain the attitude of the Emerald City is directly proportional to spin rate to the fourth power. This is discussed in greater detail in Chapter 4. Another reason behind this limit is human endurance. Most humans cannot endure extended periods of rotation at rates higher than 1 rpm¹². Although there is no universal agreement on this limit, 1 rpm was chosen as it was the most conservative limit found. To

Table 5.1 - Possible Torus Geometries

conserve mass, providing a g-level of only .8 g in the torus was considered. This lower gravity would hopefully have only minor effects on the crew. Even lower gravity levels could be used, which would reduce the mass further, but more

Crew of 1000						
major radius (m)	minor radius (m)	%change in G top-bot	outer radius (m)	n for .8g (rpm)	n for .7g (rpm)	n for .6g (rpm)
500	44.2	17.7	544	1.15	1.07	0.99
540	42.5	15.7	582	1.11	1.04	0.96
580	41.0	14.1	621	1.07	1.00	0.93
620	39.6	12.8	660	1.04	0.97	0.90
660	38.4	11.6	698	1.01	0.95	0.88
700	37.3	10.7	737	0.99	0.92	0.85

Crew of 500						
major radius (m)	minor radius (m)	%change in G top-bot	outer radius (m)	n for .8g (rpm)	n for .7g (rpm)	n for .6g (rpm)
500	31.2	12.5	531	1.16	1.09	1.01
540	30.0	11.1	570	1.12	1.05	0.97
580	29.0	10.0	609	1.08	1.01	0.94
620	28.0	9.0	648	1.05	0.98	0.91
660	27.2	8.2	687	1.02	0.95	0.88
700	26.4	7.5	726	0.99	0.93	0.86

information on the effects of long term exposure to lower gravity levels is needed before a lower g-limit can be set.

Another factor that contributes to the mass of the torus is the fact that it must hold an atmosphere. If a stressed skin is used, the necessary skin thickness and structural mass (M_{ss}) of a torus, with major radius R and minor radius r , is found using the formulas shown on the top of the next page¹³. The first two formulas find the skin thicknesses needed to withstand the principal stresses on the surface of the torus. Generally, t_{hoop} is greater than $t_{meridional}$, so t_{hoop} is used to find the structural mass. Structural mass is calculated for several configurations later in this chapter using the working stress (σ_w) and density (ρ) of

$$t_{meridional} = \frac{P_{atm} r}{\sigma_w}$$

$$t_{hoop} = \frac{\frac{P_{atm}}{2} \frac{r}{R} + \frac{P_g}{\pi} R}{\sigma_w - \rho R} R \quad (5.2)$$

$$M_{ss} = 4\pi^2 r R t_{hoop} \rho$$

aluminum. P_g is the pressure due to the load distribution inside the torus. One way to reduce the structural mass is to lower the atmospheric pressure (P_{atm}) inside. Doing this would also result in effects similar to living at higher altitudes on Earth: the coughing mechanism would be less effective, a normal speaking voice would not carry as far, boiling temperature would be lowered, etc. Since structural mass is relatively minor compared to the whole ship, a pressure of one atmosphere is used in the crew section for all calculations.

5.3 RADIATION AND SHIELDING

The principle risk of living in space is from radiation induced cancer. The National Council on Radiation Protection and Measurements¹⁴ has recommended a career limit for whole body exposure with a lifetime three percent excess risk of fatal cancer. Figure 5.2 is based on age at the start of exposure with a ten year career assumed. This recommendation, however, is made not for exploratory missions, such as a Mars mission or those that would be undertaken by the Emerald City, but for multiple missions of approximately 90 days over a 10 year period. What is needed for

Project WISH is a limit for constant exposure.

Table 5.2 shows the limits recommended for constant public and occupational exposure in the United States. The occupational annual exposure limit of 5 rem per year would be the limit used on the Emerald City.

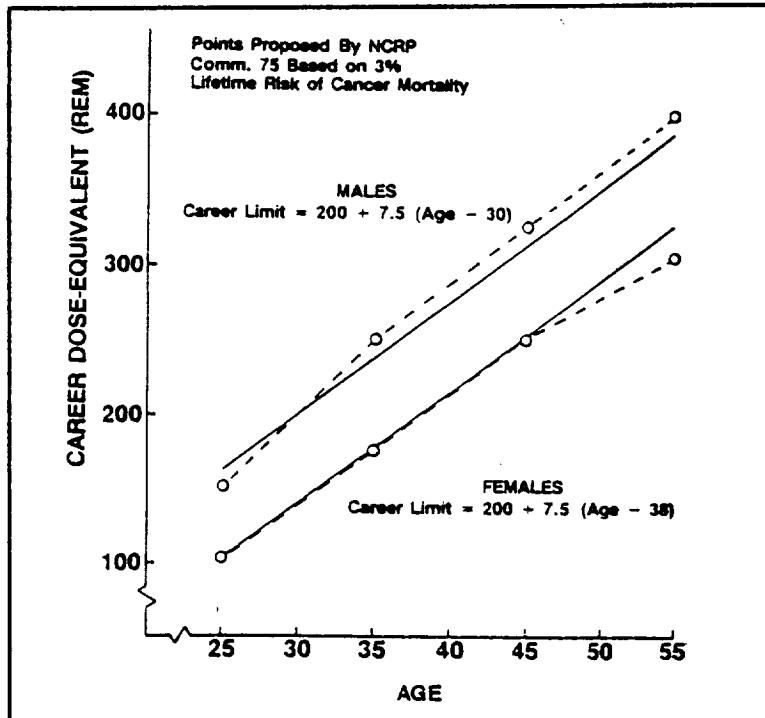


Figure 5.2 - Career Limit vs. Age

There are four major sources of radiation for Project WISH: galactic cosmic radiation, radiation from solar flare events, the propulsion system, and the power system. Of these four, only the last two can be reduced by moving the source away from the crew or by covering the source with a shield. Cosmic rays are present throughout the

Table 5.2 - Continuous Dose Limits

Occupational	
Annual	5.0 rem
Lifetime (guideline)	Age*1.0 rem
Planned or special emergency	10.0 rem
Public	
Annual, continuous	0.1 rem
Annual, occasional	0.5 rem

solar system at relatively constant intensities, decreasing only during solar flare activity. Unshielded dose rates from cosmic rays are estimated to be from 30 to 50 rem per

year¹⁵, while large solar flares are capable of delivering doses in excess of 1000 rem in only a week¹⁶. Since shielding these sources is impossible, the only way to protect from them is to shield the crew section. Radiation from the power system and the gaseous uranium core of the propulsion system can be attenuated by separating them from the crew and by partial shielding (see Figure 5.3). Unfortunately, the expanding plume of exhaust from the gas-

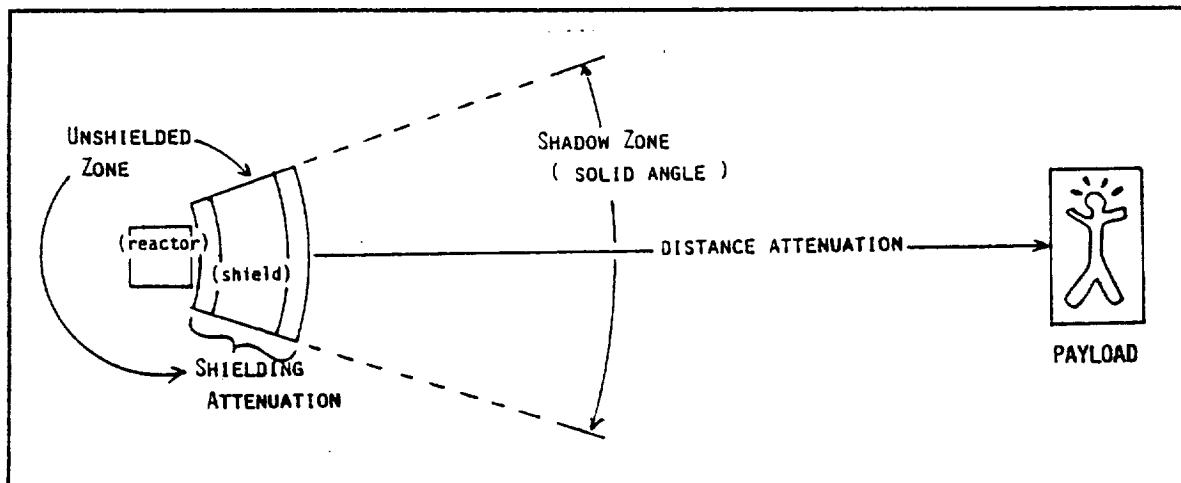


Figure 5.3 - Method of Partial Shielding

core rocket contains fission fragments that emit gamma radiation back towards the crew section. Increasing the distance between the crew and the nozzle exit will reduce the dose rate, but structural limits will only allow so much separation. The only other means of attenuation is to shield the crew section. The actual dose rate was calculated with the parameters of the gas-core engine from Chapter 3 using the formulas given by Charles Masser¹⁷. It is primarily dependant on the amount of separation between the crew and the engine, and the amount of time that fission fragments

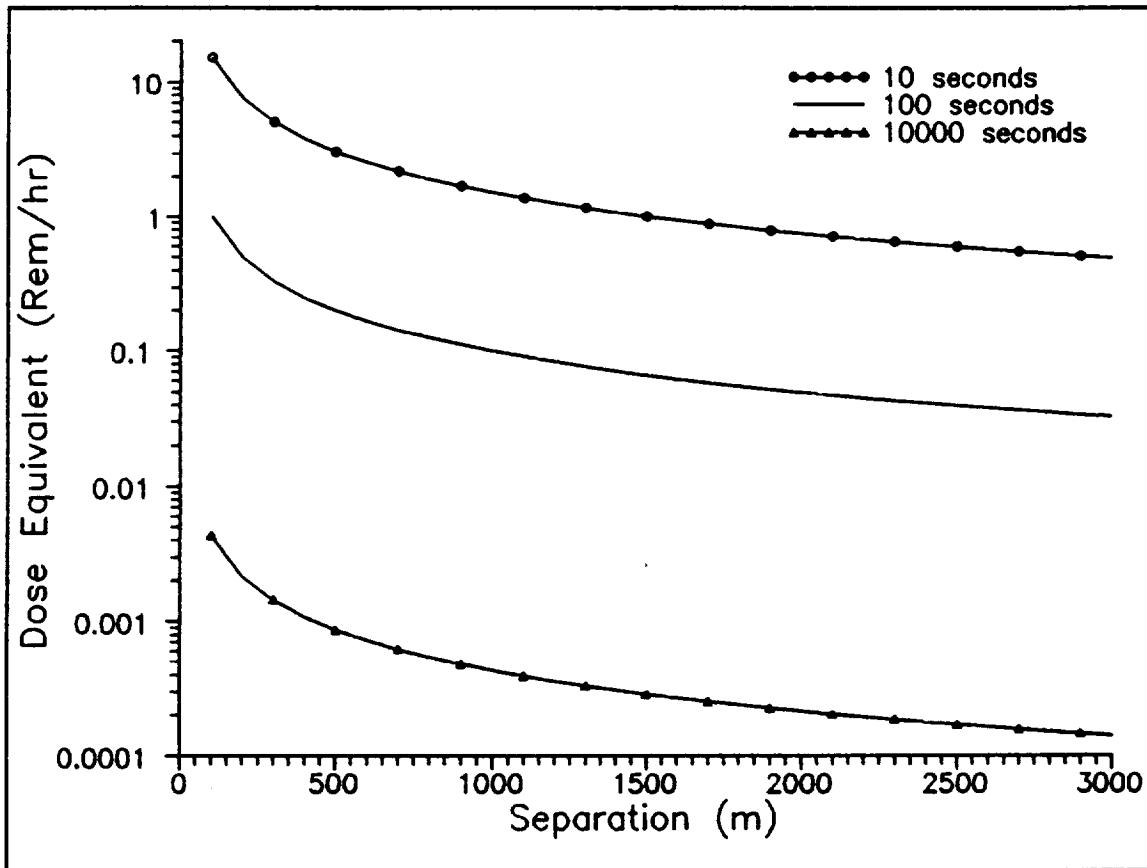


Figure 5.4 - Dose Rate vs. Separation for Varying Fission Fragment Retention Times

remain in the core before exiting the nozzle. Figure 5.4 shows this relationship for three different fission fragment retention times. The only estimate for the fission fragment retention time of the gas-core engine comes from Masser, who estimates it to be about 100 seconds. Note that the numbers in Figure 5.4 are only for one engine. It has been assumed that for the case of multiple engines, the dose rate will be additive. Although this assumption is probably not accurate, it is one that had to be made because of the limited knowledge of radiation by the members of this project.

Galactic cosmic radiation is considered to be the primary source of radiation because it is always present and cannot be

shielded at the source. No matter what their intensity, solar flares and engine exhaust will only be present for periods of about a week or two at a time. Because of this, the selection of a primary form of shielding was based on protecting against galactic cosmic radiation. The most common method of shielding is passive shielding. Passive shielding, known to be effective, simply puts a physical barrier between the source and the target. A more theoretical type of shielding is active shielding. It uses either an electromagnetic or electrostatic field to repel incoming radiation. A drawback common to both field types is that, depending on how much power they receive, they only shield radiations up to a certain energy level. Electrostatic fields were eliminated because a potential on the order of 3 GV is needed on the surface of the torus¹⁸. This potential would limit extra-vehicular activity and also generate lethal bremsstrahlung radiation fields inside the torus. An electromagnetic shield was rejected because higher energy radiation could become trapped inside the field. This would create something similar to the Van Allen belts around the Earth only much more dangerous considering the smaller distances involved. Another common failing of the shields is that they only stop charged particles. Gamma rays and neutrons, the more destructive types of radiation, are not affected.

With only passive shielding remaining, materials that could best attenuate radiation and still save mass were explored. Townshend compares different materials and finds liquid hydrogen to be

very effective¹⁹. Liquid hydrogen is more effective than other materials because it contains no neutrons for the incident radiation to scatter upon collision. Table 5.3 shows that 100 grams per square centimeter will reduce the dose to below 5 rem per year. One hundred grams per square centimeter of liquid hydrogen corresponds to a shield thickness of 14 meters. The mass of this type of shield, as well as the structural mass, is found for four different torus configurations in Table 5.4. Notice that even if the crew size is cut in half, the masses for the torus do not significantly drop. This is because of the geometrical nature of a torus, a large volume change results in a relatively minor change in surface area.

5.4 CONCLUSION

Even though all the considerations in this chapter have not been solved, enough has been determined to create a pattern that can be used to make an initial design for the Emerald City. The results of research in the areas of biospherics, microgravity, radiation, and other fields not yet considered will set the limits that help finalize any design. The information presented in this chapter will be used for a preliminary design of the Emerald City for two particular missions, which may be found in Chapter 6.

Table 5.3 - Solar Minimum Galactic Cosmic Ray Depth Dose Equivalent in Tissue as a function of Particle Type and LH₂ Shield Thickness

thickness (gm/cm ²)	dose equivalent, rem/yr, from				
	neutrons	protons	alpha's	HE	total dose
skin dose equivalent (0 cm depth)					
0.0	0.0	9.4	6.7	101.6	117.7
3.0	0.2	6.6	2.7	31.8	41.3
10.0	0.6	7.8	1.5	6.3	16.2
25.0	0.8	8.1	0.4	0.4	9.7
50.0	0.7	6.6	0.1	<.1	7.4
75.0	0.6	4.8	<.1	<.1	5.4
100.0	0.4	3.3	<.1	<.1	3.8
BFO dose equivalent (5 cm depth)					
0.0	1.4	8.0	2.9	43.0	61.1
3.0	1.8	8.8	2.2	21.2	34.1
10.0	1.9	9.6	1.2	4.4	17.2
25.0	1.7	9.4	0.1	0.3	11.7
50.0	1.3	7.4	<.1	<.1	8.7
75.0	0.9	5.3	<.1	<.1	6.2
100.0	0.7	3.6	<.1	<.1	4.3

Table 5.4 - Structural and Shield Mass Estimates

crew size	major radius	minor radius	surface area	shield mass	structural mass	skin thickness
	(m)	(m)	(m ²)	(kg)	(kg)	(cm)
1000	500	44.2	8.725e+05	8.725e+08	4.101e+07	1.741
1000	700	37.3	1.031e+06	1.031e+09	5.052e+07	1.815
500	520	30.6	6.282e+05	6.282e+08	2.407e+07	1.419
500	700	26.4	7.296e+05	7.296e+08	3.027e+07	1.537

CHAPTER 6

REPRESENTATIVE MISSION DESIGN

6.0 INTRODUCTION

Once the methodologies of the previous chapters have been formulated, two sample missions were examined in order to obtain some preliminary sizing and mass estimates for the Emerald City. A Saturn Envelope mission and the currently popular Earth-to-Mars mission were chosen as representative scenarios for this preliminary design. The design for these missions were determined by incorporating the orbital mechanics, propulsion, attitude control and human factors subsystems. Orbital mechanics (Chapter 2) was used to determine the ΔV 's required for the selected missions. The propulsion system study (Chapter 3) was used to determine the number of engines and the total engine and propellant masses. These were then used to size the Emerald City in terms of volume of propellant, engine spacing and location, length of central pole, etc. Human factors (Chapter 5) was used to determine the sizing of the torus, and the attitude control study (Chapter 4) was used to calculate the control thruster requirements. With all of the work laid down in the previous chapters in mind, it is now possible to proceed with the design of both missions.

6.1 PROCEDURE

The procedure that was followed in the design of these missions is listed sequentially as follows.

1. Obtain the ΔV required for each mission from orbital mechanics.
2. Set values for the specific impulse, I_{sp} , and the thrust per engine, F_i , for the propulsion system. The mass of each engine, m_i , is then found from the computer program of Appendix B.
3. Determine the torus mass, m_{torus} , from the masses of the biosphere, the shield, and the torus structure. These masses are dependant upon the number of crew members selected. The dry mass, m_{dry} , is then estimated by making allowances for the engine, cargo, and remaining subsystem masses.
4. Calculate the number of engines required and the total engine mass, m_e , for each mission.
5. Calculate the payload mass, m_l , for the missions. This mass is defined as $m_{dry} - m_{torus} - m_e$ and includes cargo as well as other systems that have yet to be sized (heat rejection, power, tankage, etc.).
6. Calculate the total initial mass, m_0 , and the propellant mass, m_p . The propellant mass ratio, m_p / m_0 , and the payload mass ratio, m_l / m_0 , are then found.
7. Calculate the volume of propellant required for the mission, V_p . Then, by estimating a stem radius, r_p , the height of propellant, and hence the minimum stem length, h_p , can be found.

Neptune and Pluto cannot be reached at all in flight times of up to five years with this ΔV ceiling. It should be noted that many of the transfers to Saturn can be made with ΔV 's considerably less than 50 km/s round trip, but for this mission, it was assumed that the Emerald City was in a poor orientation (ΔV -wise) with Saturn and that a three year flight time was essential. A possible motivation for such a mission might be that the Emerald City is required to support the first manned exploration of Saturn's moon Titan, and that the planetary alignments and limitations on the interplanetary transfer ship require a particular launch date from the Martian colony and arrival time at Saturn.

For this mission, the individual ΔV 's and the powered-flight times required for the four separate burns were not considered, but only the total ΔV and powered-flight time. The number of engines was found based on these total values and a given total powered-flight time of 20 days, but it should be kept in mind that the powered-flight times would not be the same for all four burns, even if the ΔV required would be the same. This is because the mass of the Emerald City is smaller for each of the burns, and hence the longest powered-flight time would be the first one.

The results for the Saturn mission can be found in Tables 6.1. Some important values to note are the total initial mass, 4.16×10^9 kilograms, the number of engines, 172, the torus radius, 700 meters, and the height of the pole section, 1270 meters. The payload mass ratio for this mission was found to be 0.083, or 8.3% of the total initial mass is payload. It must be remembered,

however, that the payload mass as defined here is the mass of the cargo plus the mass for any other systems that were not considered during Phase II (power systems, thermal rejection systems, tankage mass, etc.).

6.2.2 Earth-to-Mars Mission

The second mission that was examined was a transfer from 1 AU to Mars. This mission represents a more common mission that the Emerald City might be required to undertake, perhaps carrying new colonists and supplies that had been shuttled to the Emerald City, just outside the Earth's sphere of influence, to the ever expanding Martian colonies. For this mission, the ΔV required was broken down into the departure and arrival ΔV 's. The mission was scheduled to leave Earth on November 7, 2050 and the flight time was determined by minimizing the ΔV for this launch date using the MULIMP program. The ΔV 's were found to be 5.1 km/s and 7.5 km/s for a total ΔV of 12.6 km/s, and the flight time was found to be 1.52 years. The first powered-flight time was set at 5 days and the number of engines required was determined. Then, keeping this number of engines constant, the second powered-flight time was found. From Table 6.1, it can be seen that the results of this were found to be 33 engines, a 5 day initial powered-flight time, and a 6.53 day terminal powered-flight time. Some of the other important design values for this mission are the initial mass, 1.295×10^9 kg, the torus radius, 700 meters, and the pole height, 569 meters.

Table 6.1 - Summary of Design Variables for Sample Missions

	Saturn Mission	Earth to Mars
People	1000	500
ΔV_{total} (km/s)	50	12.6
ΔV_1 (km/s)	-	5.1
ΔV_2 (km/s)	-	7.5
F_i (Newtons)	4.4×10^5	4.4×10^5
I_{sp} (seconds)	5000	5000
$t_{pr,\text{total}}$ (days)	20	11.53
$t_{pr,1}$ (days)	-	5
$t_{pr,2}$ (days)	-	6.53
number of engines	172	33
m_{dry} (kg)	1.5×10^9	1×10^9
m_{torus} (kg)	1.111×10^9	7.746×10^8
m_v (kg)	4.4376×10^7	8.514×10^6
m_l (kg)	3.457×10^8	2.165×10^8
m_p (kg)	2.658×10^9	2.947×10^8
m_n (kg)	4.16×10^9	1.295×10^9
m_l / m_n	0.083	0.167
m_p / m_n	0.639	0.228
V_{LH2} (m ³)	3.742×10^7	4.151×10^6
r_{pole} (m)	100	50
h_p (m)	1200	528
h (m)	1270	569
R (m)	700	700
r_{min} (m)	37	26
I_x (kg m ²)	5.6144×10^{14}	3.8061×10^{14}
I_x, I_y (kg m ²)	9.9568×10^{14}	2.1731×10^{14}
r (I_x / I_y)	0.563876	1.75154
max/min g-levels	0.8/0.72	0.8/0.74
n (spin rate, rpm)	0.99	0.99

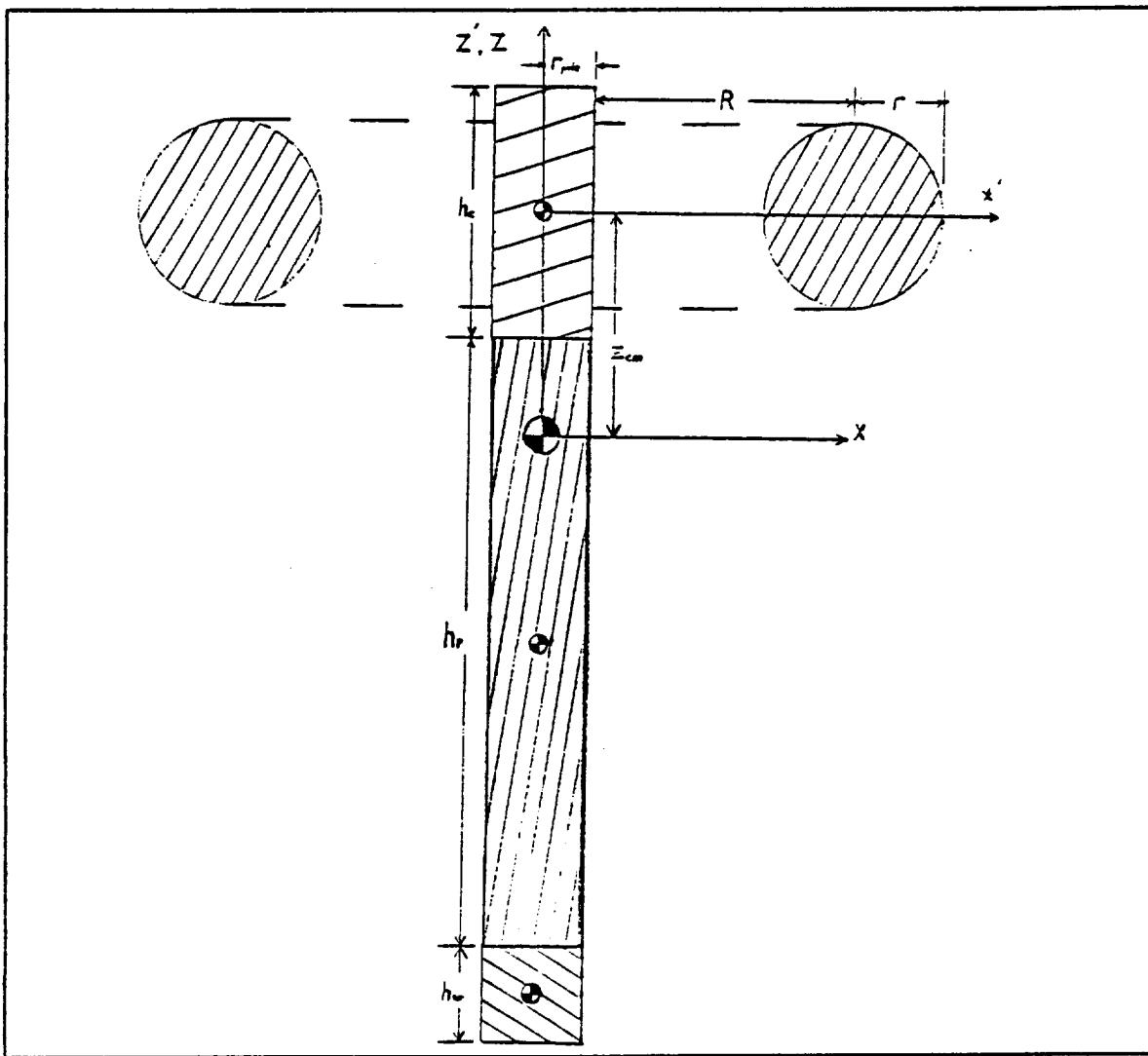


Figure 6.1 - Schematic of the Emerald City

6.2.3 Attitude Control System Requirements

An attitude control system was designed for the two particular missions examined for a sample initial disturbance and a sample thruster configuration. Using the methodology developed in Chapter 4, the root-mean-square power, propellant mass, maximum thrust, and control time was determined, as may be seen in Table 6.2. Also, the state response, control torque profile, and thrust profile for

the Saturn Envelope mission configuration are shown in Figures 6.2-6.4 for the sample thruster configuration shown in Figure 6.5.

Table 6.2 - Attitude Control System Requirements

I_x / I_y	0.56	1.75
Initial Disturbance	$[\theta_1, \theta_2, \dot{\theta}_1, \dot{\theta}_2] = [.1 .1 .1n .1n]$	
P_{rms} (watts)	6.176×10^{12}	7.86×10^{11}
$m_p,control$ (kg)	2.105×10^7	3.458×10^6
$F_{control,max}$ (N)	2.988×10^9	1.911×10^9
$t_{control}$ (s)	~ 100	~ 100

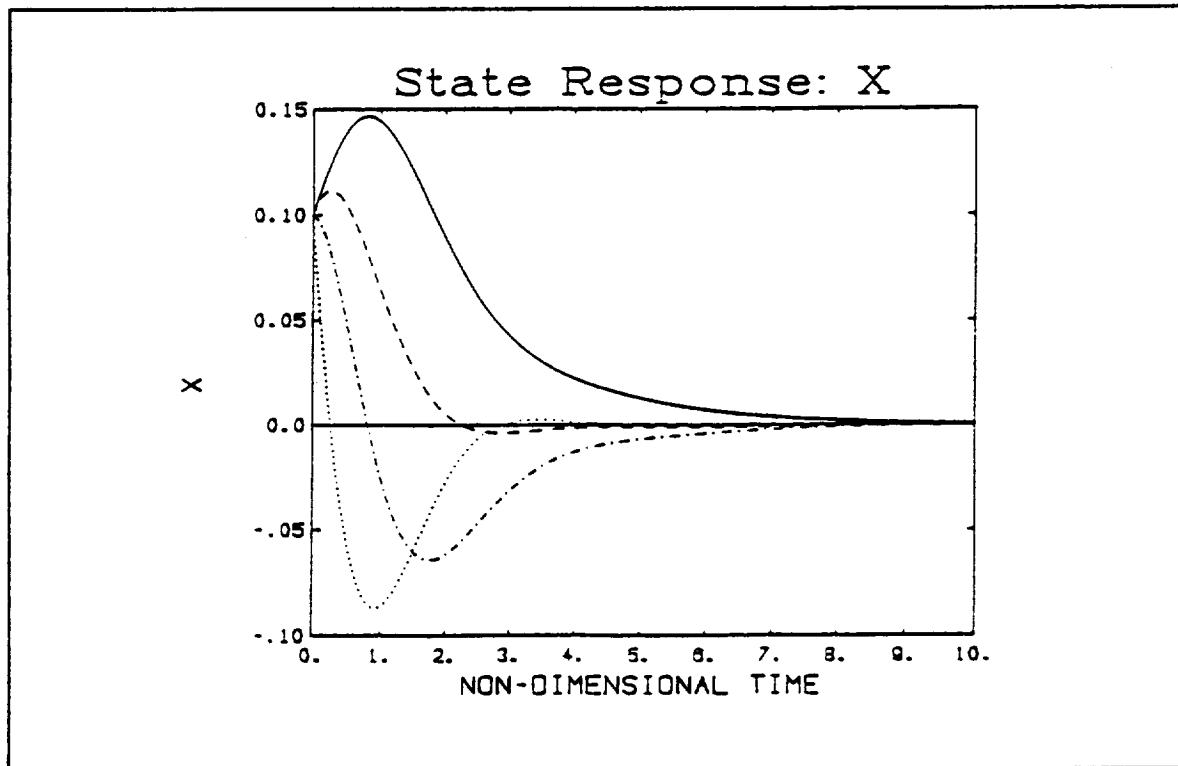


Figure 6.2 - Non-Dimensional State Response ($r = 0.5$)

Control Torques: $\tau = GX$

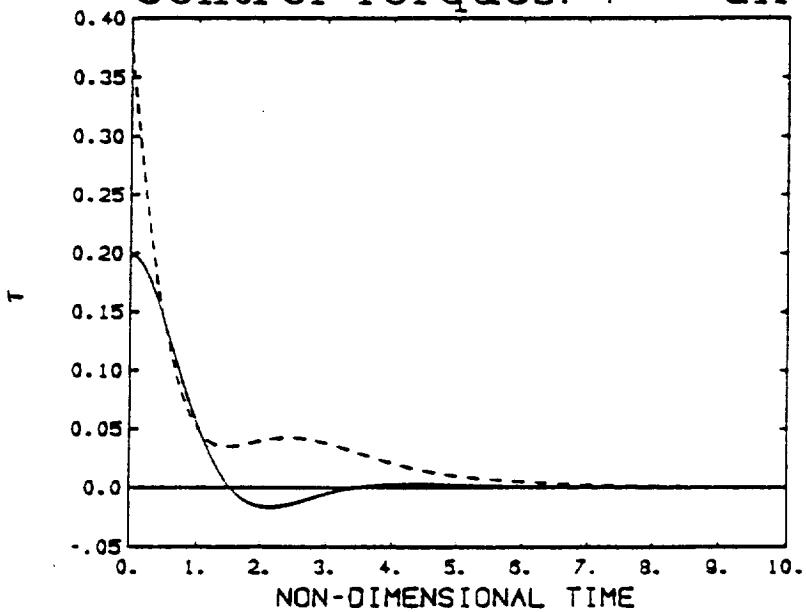


Figure 6.3 - Control Torque Profile ($r = 0.5$)

Non-dimensional Thrusts: $F = \text{inv}(D)\tau$

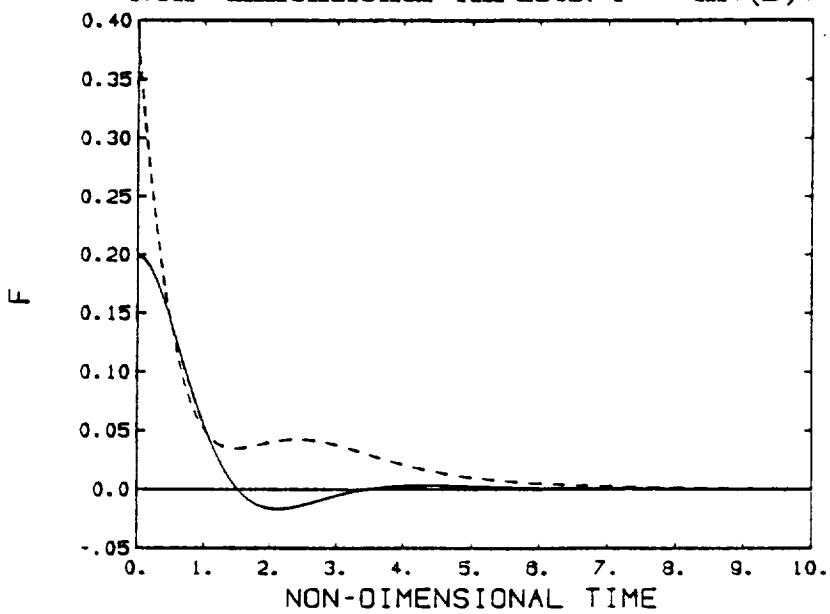


Figure 6.4 - Non-dimensional Thrust Profile ($r = 0.5$)

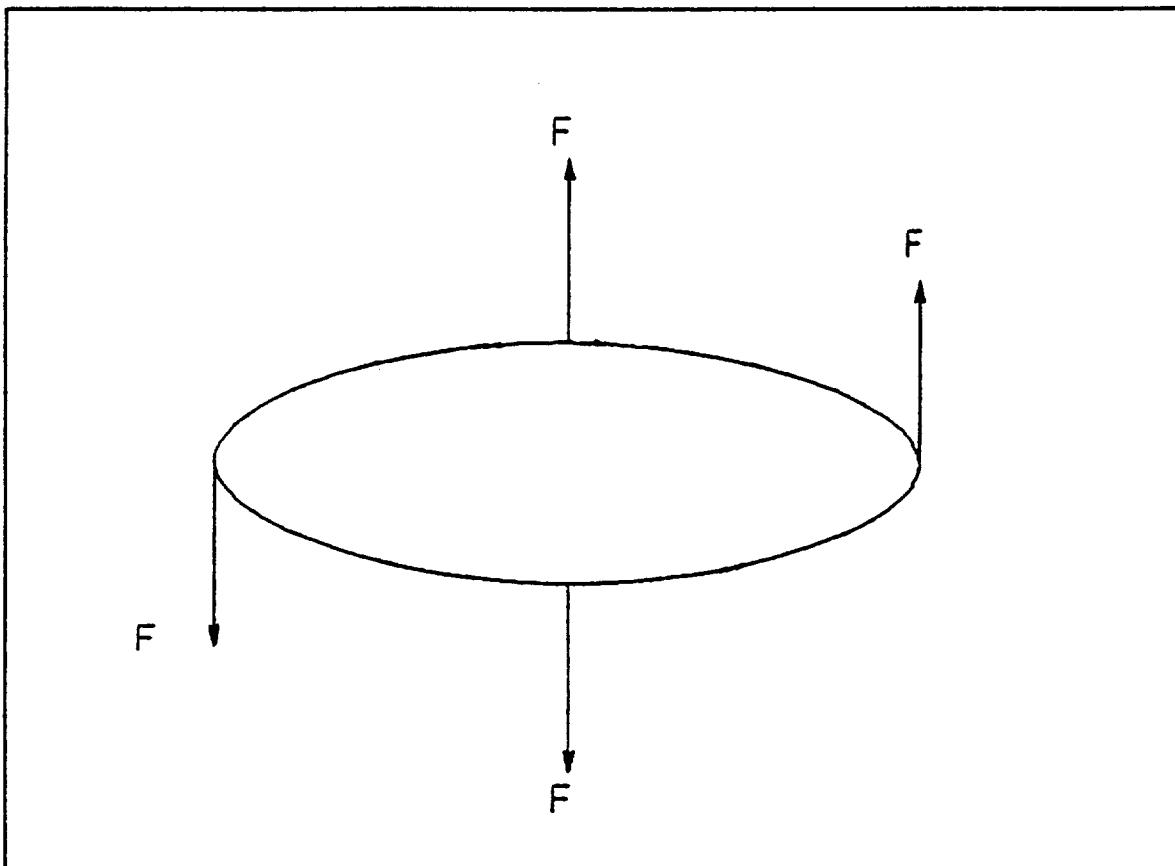


Figure 6.5 - Sample Thruster Configuration

6.3 CONCLUSION

In this chapter, two particular missions were examined for the Emerald City. However, using the methodology established here, a wide variety of missions may be looked at and the configuration for the Emerald City may be determined. In the future, different mission parameters, such as crew size, ΔV requirements, sample initial disturbances, attitude thruster configurations, etc..., may be examined. It is felt that this methodology is the main accomplishment of the Phase II design of Project WISH.

CHAPTER 7
CONCLUSION

7.0 PROJECT SUMMARY

Phase II of Project WISH was able to accomplish a great deal towards the design of the Emerald City. In orbital mechanics, a nominal orbit of 4 AU's was selected, and the operational envelope for the Emerald City was determined. An open-cycle gas-core nuclear thermal propulsion system was chosen as the main propulsion unit, and a detailed study was conducted on this type of engine. For attitude control, a methodology was established to determine the thruster requirements needed to damp out a disturbance experienced by the Emerald City. Human factors looked at the problems of life support, artificial gravity, and radiation shielding. Biospheres were examined as the primary method to sustain life, while the torus size requirements were determined for the different levels of gravity that the crew would need. Radiation shielding proved to be one of the major design problems encountered, and mass estimates were obtained for shielding from cosmic radiation. The ultimate result of the Phase II study was the generation of Tables 6.1 and 6.2. These tables incorporated information from all of the subsystems studied, and provide data on the estimated size and mass requirements of the Emerald City. By examining these figures, one can realize the magnitude of a ship such as the Emerald City.

concessions to the unknown, we had best frankly recognize that irrational faith in the value of a new capability often plays an essential part in the early evolution of a new concept. Certainly, at that point, the lack of a recognized application is a demonstrably unsound basis for the concept's rejection."

Table 7.1 - Envisioned Time Line for Project WISH

- 1989 - President Bush announces Mars Initiative to reach the Red Planet in 30 years.
 - 1991 - NASA presents a program to send sensing probes throughout the solar system. Projects include the return to the inner solar system, exploration of the asteroid belt, and further missions to the outer planets.
 - 1998 - Space Station Freedom becomes operational.
 - 2001 - Heavy Lift Launch Vehicle makes its maiden flight.
 - 2004 - Construction begins on a near-geosynchronous Earth orbiting space station.
 - 2009 - U.S. returns to the moon.
 - 2011 - Construction begins on the Moon Base.
 - Maiden flight of National Aerospace Plane.
 - 2015 - Moon Base becomes fully operational.
 - 2019 - First manned mission to Mars.
 - 2023 - First living modules constructed on Mars.
 - Construction begins on Reusable Interplanetary Ships (R.I.S.'s) for carrying personnel and cargo.
 - 2028 - Mars Base becomes fully operational.
 - 2040 - Implementation of Project WISH.
 - 2050 - The Emerald City becomes operational.
-

APPENDIX A
EQUATIONS FOR ΔV MINIMIZATION PROBLEM

The objective function given for the ΔV minimization problem set up in Chapter 2 was given by Equation 2.4

$$\Delta V_T = \Delta V_1 + \Delta V_2 = \vec{V}_1 - \vec{V}_o + \vec{V}_f - \vec{V}_2 \quad (2.4)$$

where ΔV_1 and ΔV_2 are the velocity changes along the thrust vector direction, which will be kept constant during each powered-flight phase. The constraints were given in Chapter 2 as

1. $t_{ff} + t_{pr1} + t_{pr2} < TOF_{max}$
2. $a_0 < a_{0,max}$
3. $t_{pr1} + t_{pr2} < t_{pr,max}$
4. $x_{f,EC} = x_{f,T0}$.
5. $a_0, t_{pr1}, t_{pr2}, t_{ff} > 0.$

Thus, the problem is to determine the relationships between these values and the design variables of the problem.

Since a circular nominal orbit and target planet orbit has been assumed, v_0 and v_f are given by the formulas for circular orbital velocity,

$$v_0 = \sqrt{\frac{\mu}{r_0}} \quad (A.1)$$

$$v_f = \sqrt{\frac{\mu}{r_f}} \quad (A.2)$$

which are known for a given nominal orbit and target planet. However, finding the velocities v_1 , the velocity at the end of the first powered-flight phase, and v_2 , the velocity at the beginning of the second powered-flight phase, is more involved. To find the equations for these velocities, the kinematic relationship

$$dv = a \cdot dt \quad (\text{A.3})$$

was integrated along the direction of thrust, with an acceleration term in this direction given by

$$a(t) = \frac{a_o}{1 - \frac{a_o t}{I_{sp} g}}. \quad (\text{A.4})$$

This term arises from the fact that as the Emerald City is burning with a constant thrust, it is expending mass, and thus the acceleration will increase with time according to Equation A.4. Inserting Equation A.4 into Equation A.3 and performing the integration yields

$$v = v_i - I_{sp} g \ln\left(1 - \frac{a_o t_{pr}}{I_{sp} g}\right), \quad (\text{A.5})$$

which becomes

$$\Delta V_1 = v_{1F} - v_{oF} = - I_{sp} g \ln\left(1 - \frac{a_o t_{pr1}}{I_{sp} g}\right) \quad (\text{A.6})$$

for the first powered-flight portion of the transfer. Similarly, for the second powered-flight portion of the transfer, the velocity change is given by

$$\Delta V_2 = v_{f_F} - v_{2_F} = -I_{sp}g \ln\left(1 - \frac{a_{o2} t_{pr2}}{I_{sp}g}\right)$$

where (A.7)

$$a_{o2} = \frac{a_o}{1 - \frac{a_o t_{pri}}{I_{sp}g}}.$$

The subscript F in Equations A.6 and A.7 denotes the components of the respective velocity vectors projected along the thrust direction (it is assumed that the thrust angles, $\beta_{1,2}$, will not be changed during a powered-flight phase). It can easily be seen that by using Equations A.6 and A.7, the objective function of Equation 2.4 can be written as

$$\Delta V_r = -I_{sp}g \left[\ln\left(1 - \frac{a_o t_{pri}}{I_{sp}g}\right) + \ln\left(1 - \frac{a_{o2} t_{pr2}}{I_{sp}g}\right) \right]. \quad (A.8)$$

where a_{o2} is not an independent variable, but given in Equation A.7.

The application of the constraint functions needed many more equations and relationships. First, continuing in the same manner as was used to find Equation A.5, the relationship

$$dx = v dt \quad (A.9)$$

was integrated with the results from Equation A.5 inserted for v , and the result was found to be

$$x_{1,f} = x_{o,2} + v_{o,2} t_{pri,2} + \frac{(I_{sp}g)^2}{a_{o,o2}} \Phi_{1,2}$$

where (A.10)

$$\Phi_{1,2} = \left(1 - \frac{a_{o,o2} t_{pri,2}}{I_{sp} g}\right) \left[\ln\left(1 - \left(\frac{a_{o,o2} t_{pri,2}}{I_{sp} g}\right) - 1\right) + 1 \right] + 1.$$

Equation A.10 yields the position along the direction of the thrust vector and the subscript 1,f means at position 1 or f, etc. Thus, armed with Equations A.5, A.10, and some fundamental relationships from astrodynamics, the constraints can be related to the design variables of the problem in the following manner. First, the inertial X- and Y-components of the velocity and radius vectors at the end of the first powered-flight phase can be found by applying coordinate rotation matrices to Equations A.5 and A.10. These equations are given by

$$\begin{aligned} v_{1x} &= -\sqrt{\frac{\mu}{r_o}} \sin\theta_o - I_{sp}g \sin(\beta_1 - \theta_o) \ln(1 - \frac{a_o t_{pri}}{I_{sp}G}) \\ v_{1y} &= \sqrt{\frac{\mu}{r_o}} \cos\theta_o - I_{sp}g \cos(\beta_1 - \theta_o) \ln(1 - \frac{a_o t_{pri}}{I_{sp}G}) \\ v_1 &= \sqrt{v_{1x}^2 + v_{1y}^2} \end{aligned} \quad (\text{A.11})$$

and

$$\begin{aligned} r_{1x} &= r_o \cos\theta_o - \sqrt{\frac{\mu}{r_o}} t_{pri} \sin\theta_o + \frac{(I_{sp}G)^2}{a_o} \sin(\beta_1 - \theta_o) \Phi \\ r_{1y} &= r_o \sin\theta_o + \sqrt{\frac{\mu}{r_o}} t_{pri} \cos\theta_o + \frac{(I_{sp}G)^2}{a_o} \cos(\beta_1 - \theta_o) \Phi \\ \Phi &= (1 - \frac{a_o t_{pri}}{I_{sp}G}) [\ln(1 - \frac{a_o t_{pri}}{I_{sp}G}) - 1] + 1 \\ r_1 &= \sqrt{r_{1x}^2 + r_{1y}^2} \end{aligned} \quad (\text{A.12})$$

where the known variables are r_o and I_{sp} and the design variables are θ_o , t_{pri} , a_o , and β_1 . Once the velocity and position vectors at the initial point of the free-flight trajectory (point 1) are known, the transfer orbit is defined by the following equations:

$$e_x = \frac{1}{\mu} [(v_1^2 - \frac{\mu}{r_1}) r_{1x} - (r_{1x} v_{1x} + r_{1y} v_{1y}) v_{1x}]$$

$$e_y = \frac{1}{\mu} [(v_1^2 - \frac{\mu}{r_1}) r_{1y} - (r_{1x} v_{1x} + r_{1y} v_{1y}) v_{1y}] \quad (A.13)$$

$$e = \sqrt{e_x^2 + e_y^2}$$

$$\gamma_0 = \cos^{-1}(\frac{e_x}{e}) \quad (\text{quadrant}) \quad (A.14)$$

$$E = \frac{v_1^2}{2} - \frac{\mu}{r_1} \quad (A.15)$$

$$a = -\frac{\mu}{2E} \quad (A.16)$$

$$\gamma_1 = \cos^{-1}(\frac{a(1 - e^2) - r_1}{e r_1}) \quad (\text{quadrant}) \quad (A.17)$$

$$h = \sqrt{a(1 - e^2)\mu} \quad (A.18)$$

In the above equations, e is the eccentricity of the transfer orbit, τ_0 is the direction of the eccentricity vector, E is the specific energy of the transfer orbit, a is the semi-major axis of the transfer orbit, τ_1 is the true anomaly at the end of the first powered-flight time, and h is the angular momentum of the transfer orbit. Once the transfer orbit is defined through these equations, the variables at the terminal free-flight point (point 2) may be calculated. The design variable that was designated was γ_2 , which is the true anomaly at point 2. This then defines the free-flight time of the transfer according to

$$t_{ff} = \sqrt{\frac{a^3}{\mu}} [2\pi k + (E_2 - e \sin E_2) - (E_1 - e \sin E_1)] \quad (\text{A.19})$$

where E is the eccentric anomaly, defined by

$$E_n = \cos^{-1} \left(\frac{e + \cos \gamma_n}{1 + e \cos \gamma_n} \right) \quad (\text{A.20})$$

and k is the number of times the periapsis is passed during the transfer. The rest of the values at point 2 are given by

$$x_2 = \frac{a(1 - e^2)}{1 + e \cos \gamma_2} \quad (\text{A.21})$$

$$v_2 = \sqrt{2(E + \frac{\mu}{x_2})} \quad (\text{A.22})$$

$$\theta_2 = [\frac{\gamma_o + \gamma_2}{360^\circ} - \text{INTEGER}(\frac{\gamma_o - \gamma_2}{360^\circ})] \cdot 360^\circ \quad (\text{A.23})$$

$$\phi_2 = \cos^{-1} \left(\frac{h}{x_2 v_2} \right) \quad (\text{quadrant}) \quad (\text{A.24})$$

$$\begin{aligned} x_{2x} &= x_2 \cos \theta_2 \\ x_{2y} &= x_2 \sin \theta_2 \end{aligned} \quad (\text{A.25})$$

$$\begin{aligned} v_{2x} &= -v_2 \sin(\theta_2 - \phi_2) \\ v_{2y} &= v_2 \cos(\theta_2 - \phi_2). \end{aligned} \quad (\text{A.26})$$

The equations governing the final powered-flight phase of the trajectory are found by applying coordinate rotation matrices to Equations A.5 and A.10, similar to the way that Equations A.11 and A.12 were obtained. These equations were found to be

$$\begin{aligned} v_{fx} &= -v_2 \sin(\theta_2 - \phi_2) - I_{sp}g \sin(\beta_2 - \theta_2) \ln\left(1 - \frac{a_{o2}t_{pr2}}{I_{sp}g}\right) \\ v_{fy} &= v_2 \cos(\theta_2 - \phi_2) - I_{sp}g \cos(\beta_2 - \theta_2) \ln\left(1 - \frac{a_{o2}t_{pr2}}{I_{sp}g}\right) \end{aligned} \quad (\text{A.27})$$

and

$$\begin{aligned} r_{tx} &= r_2 \cos\theta_2 - v_2 t_{pr2} \sin(\theta_2 - \phi_2) + \frac{(I_{sp}g)^2}{a_{o2}} \sin(\beta_2 - \theta_2) \Phi_2 \\ r_{ty} &= r_2 \sin\theta_2 + v_2 t_{pr2} \cos(\theta_2 - \phi_2) + \frac{(I_{sp}g)^2}{a_{o2}} \cos(\beta_2 - \theta_2) \Phi_2 \quad (\text{A.28}) \\ \Phi_2 &= \left(1 - \frac{a_{o2}t_{pr2}}{I_{sp}g}\right) \left[\ln\left(1 - \frac{a_{o2}t_{pr2}}{I_{sp}g}\right) - 1\right] + 1. \end{aligned}$$

The above equations will play an important part in the determination of the constraints on the total time-of-flight and the rendezvous requirement. For the time-of-flight constraint, the constraint function is found by adding the two powered-flight times, which are design variables, to the free-flight time as found from Equation A.19. This value must then fall below the specified TOF_{\max} (three years for most cases) for the constraint to be satisfied. For the rendezvous requirement, recall from Chapter 2 that the state vector at point i, \vec{x}_i , was defined such that

$$\vec{x}_i = \{\vec{r}_i \quad \vec{v}_i\}. \quad (2.5)$$

The rendezvous constraint requires that $x_{f,EC} = x_{f,T0}$, which represents the Emerald City ending the transfer with the desired velocity and radius vectors at the target orbit. The state vector, $x_{f,EC}$, can be found from Equations A.27 and A.28, while the state vector, $x_{f,T0}$, can be determined from

$$\theta_{r,T0} = \theta_f + \sqrt{\frac{\mu}{r_p^3}} TOF \quad (A.29)$$

$$r_{x,T0} = r_p \cos \theta_{r,T0} \quad (A.30)$$

$$r_{y,T0} = r_p \sin \theta_{r,T0}$$

$$v_{x,T0} = -v_p \sin \theta_{r,T0} \quad (A.33)$$

$$v_{y,T0} = v_p \cos \theta_{r,T0}$$

With the above formulation, care must be taken in the programming of the above equations to assure that the proper quadrant is used when inverse trigonometric functions are used.

APPENDIX B

ENGINE CHARACTERISTIC CALCULATIONS

A computer program was written to calculate the important engine parameters for an open-cycle gas-core nuclear engine. This program is listed below. The equations were either obtained from Ragsdale's paper or derived from basic considerations

```
*****
program gascore
*****
* this program finds the parameters of a gas core rocket for a
* specific cavity diameter and Isp and prints the data to a file
* called engine.dat. Enjoy.
*****
dimension f(5)
open(unit=1,file="ENGINE.DAT")
GRAV=9.80665
PI=3.14159265
ATM=1.01325E5
UGC=8314
THRUST=4.4E+5
VUVC=.23
write(6,10)
10 format('1',5X,'ENTER SPECIFIC IMPULSE (Seconds)')
read*,SPIMP
write(6,40)
40 format(5X,' ENTER REACTOR CAVITY DIAMETER (Meters)')
read*,DIAM

** Calculate critical mass of Uranium 233 **
CD=3.3*DIAM
CRITM=201.836-67.0167*CD+7.70629*CD**2-.158108*CD**3-
&.0196678*CD**4+.00088141*CD**5

** Calculate mass flow rate ratio **
DOTM=5.041871E-5*(VUVC**-10.799136)

** Calculate hydrogen propellant temperature **
TH2=-294.461+4.36196*SPIMP+7.23731E-4*SPIMP**2-6.03953E-
&7*SPIMP**3
TH2=TH2+1.36261E-10*SPIMP**4-7.71588E-15*SPIMP**5

** Calculate reactor cavity pressure **

```

```

PRES=(1066.57*CRITM*((THRUST*SPIMP)**.277)*(DOTM**.1012)/
&(DIAM**3.277))**1.383

** Calculate mass flow rate from nozzle **

PDOT=THRUST/(SPIMP*GRAV)

** Calculate mass flow rate of hydrogen and uranium **

UDOT=PDOT/(DOTM+1)
H2DOT=PDOT-UDOT

** Calculate uranium temperature **

TU=140.06*((PRES*THRUST*SPIMP/DIAM)**.16)*(DOTM**.017)

** Calculate pressure chamber volume and uranium volume **

VC=1.33333*PI*((DIAM/2)**3)
VU=VUVC*VC

** Calculate hydrogen ratio of specific heats in cavity **

GAMMAC=3.84502-.000336982*TH2+1.61689E-8*TH2**2-3.66763E-
&13*TH2**3
GAMMAC=GAMMAC+4.37181E-18*TH2**4-2.65532E-23*TH2**5+
&6.49491E-29*TH2**6

** Calculate hydrogen molecular mass in cavity **

H2MMC=2.32426-.000111528*TH2+2.53066E-9*TH2**2-2.49052E-
&14*TH2**3
H2MMC=H2MMC+8.94761E-20*TH2**4

** Calculate throat conditions **

TTH=TH2/(1+((GAMMAC-1)/2))
PTH=PRES/((1+(GAMMAC-1)/2)**(GAMMAC/(GAMMAC-1)))
PTH=PTH/ATM
GAMMAT=3.84502-.000336982*TTH+1.61689E-8*TTH**2-
&3.66763E-13*TTH**3
GAMMAT=GAMMAT+4.37181E-18*TTH**4-2.65532E-23*TTH**5+
&6.49491E-29*TTH**6
H2MMT=2.32426-.000111528*TTH+2.53066E-9*TTH**2-
&2.49052E-14*TTH**3
H2MMT=H2MMT+8.94761E-20*TTH**4
ATH=PDOT*SQRT(TH2)/PRES
ATH=ATH/SQRT(GAMMAT*H2MMT*(2/(GAMMAT+1))**2
&((GAMMAT+1)/(GAMMAT-1))/UGC)
VTH=SQRT(GAMMAT*UGC*TTH/H2MMT)

** Calculate exit mach number **

```

```

      AMACH=3.00
50    ANSW=(2*(1+((GAMMAC-1)/2)*AMACH**2)/(GAMMAC+1))
&**((GAMMAC+1)/(GAMMAC-1))
      ANSW=ANSW/AMACH**2-9E4
      if(ANSW.gt.0) goto 60
      AMACH=AMACH+.05
      goto 50

**      Calculate exit conditions **

60    VE=SPIMP*GRAV
      TE=H2MMC*(VE/AMACH)**2/(UGC*GAMMAC)
      PE=PRES/((1+((GAMMAC-1)/2)*AMACH**2)**(GAMMAC/
&(GAMMAC-1)))
      PE=PE/ATM
      AE=300*ATH
      GAMMAE=1.40018-3.60774E-6*TE-2.87154E-8*TE**2+5.90601E-
&12*TE**3
      GAMMAE=GAMMAE-2.94162E-16*TE**4
      H2MME=-2.8375E-6*TE+2.01586

**      Calculate density of uranium **

      RHOU=CRITM/VU

**      Calculate diameter of uranium **

      DIAMU=2*(3*VU/4/PI)**(.3333333)

**      Calculate reactor power      **

      QR=((TU/950)**6.25)*DIAMU/PRES

**      Calculate thickness and mass of pressure shell **

      THPS=PRES*(DIAM+1.52)/(5.516E9)
      PSM=1333.33*PI*((DIAM+1.52+2*THPS)**3-(DIAM+1.52)**3)

**      Calculate mass of moderator, turbopump, nozzle, and
**      radiator **

      EMM=191.67*PI*((DIAM+1.54)**3-DIAM**3)
      TPM=.000307181*H2DOT*((1.5*PRES)**(.66667))
      ENM=52861.26*THRUST/PRES
      PR=3E-6*SPIMP+4.4E-2
      RM=145*PR*QR

**      Calculate total engine mass      **

      ENGMASS=PSM+EMM+TPM+ENM+RM

**      Calculate engine specific mass and jet power **
```

```

ALPHA=204.96*ENGMASS/(SPIMP*THRUST)
PJET=.5*THRUST*SPIMP*GRAV/1E6
** Calculate exit velocity      **
VEXIT=SPIMP*GRAV

** Calculate thrust to weight ratio **

TWR=THRUST/(ENGMASS*GRAV)
PRES=PRES/ATM
write(1,70)
70 format(' SPECIFIED VALUES:')
write(1,80)SPIMP,THRUST,VUVC,DIAM
80 format(1X,'Isp=',F8.2,' seconds',3X,'Thrust=',F11.2,' 
&Newtons',3X,'Vu/Vc=',F3.2,3X,'Dc=',F5.2,' Meters')
write(1,90)
90 format(//,1X,'CALCULATED ENGINE PARAMETERS:')
write(1,100)
100 format(//,1X,'ENGINE CAVITY CONDITIONS:')
write(1,110)TH2,TU
110 format(1X,'T(H2)=',F8.2,' Kelvin',19X,'T(U233)=',F9.2,' 
&Kelvin')
write(1,120)PRES,CRITM
120 format(1X,'Cavity Pressure=',F7.2,' Atm',13X,
'Critical Mass U233=',F6.2,' Kg')
write(1,130)VC,VU
130 format(1X,'Cavity Volume=',F5.2,' Cubic
&Meters',8X,'Uranium
&Volume=',F5.2,' Cubic Meters')
write(1,140)DIAMU,RHOU
140 format(1X,'Uranium Diameter=',F4.2,' Meters',12X,'Uranium
&Density=',F6.2,' Kg/Cubic Meter')
write(1,150)H2MMC,GAMMAC
150 format(1X,'Hydrogen Molecular
&Mass(Cavity)=',F5.3,2X,'Gamma(Cavity)=',F5.3)
write(1,160)
160 format(//,1X,'MASS FLOW RATES:')
write(1,170)DOTM,PDOT
170 format(1X,'H2-To-U233 Mass Flow Ratio=',F7.2,6X,
'Propellant Mass Flow Rate=',F6.2,' Kg/sec')
write(1,180)H2DOT,UDOT
180 format(1X,'H2 Mass Flow Rate= ',F7.3,' Kg/sec',6X,' U233
&Mass Flow Rate=',F6.3,' Kg/sec')
write(1,190)
190 format(//,1X,'ENGINE DIMENSIONS:')
write(1,200)THPS,PSM
200 format(1X,'Pressure Shell Thickness=',F5.3,' 
&Meters',3X,'Pressure Shell Mass=',F8.2,' Kg')
write(1,210)EMM
210 format(1X,'Moderator Thickness= 0.76 Meters'
&,8X,'Moderator Mass=',F9.2,' Kg')
write(1,220)TPM,ENM

```

```

220      format(1X,'Turbo Pump Mass=',F7.2,' Kg',14X,'Exhaust
&Nozzle Mass=',F7.2,' Kg')
      write(1,230)RM,ENGMASS
230      format(1X,'Radiator Mass=',F9.2,' Kg',14X,'Total Engine
&Mass=',F10.2,' Kg')
      write(1,240)
240      format(/,1X,'VARIOUS ENGINE PARAMETERS:')
      write(1,250)QR,.06*QR
250      format(1X,'Reactor Power=',F8.2,' MWatts',11X,'Radiated
&Power=',F7.2,' MWatts')
      write(1,260)ALPHA,PJET
260      format(1X,'Engine Specific Mass=',F7.5,' Kg/KWatt',
&3X,'Jet Power=',F9.2,' MWatts')
      write(1,270)TWR,PJET/QR
270      format(1X,'Thrust to Weight Ratio=',F7.5,10X,'Engine
&Efficiency=',F5.4)
      write(1,280)
280      format(/,1X,'THROAT CONDITIONS:')
      write(1,290)TTH,PTH
290      format(1X,'Throat temperature=',F8.2,' Kelvin',6X,'Throat
&pressure=',F7.2,' Atm')
      write(1,295)H2MMT,GAMMAT
295      format(1X,'Hydrogen Molecular Mass
&(Throat)=',F5.3,2X,'Gamma (Throat)=',F5.3)
      write(1,300)ATH,VTH
300      format(1X,'Throat Area=',F7.4,' Sq Meters',11X,'Throat
&Velocity=',F9.2,' Meters/sec')
      write(1,310)
310      format(/,1X,'EXIT CONDITIONS:')
      write(1,320)TE,PE
320      format(1X,'Exit temperature=',F8.2,' Kelvin',8X,'Exit
&pressure=',F5.3,' Atm')
      write(1,325)H2MME,GAMMAE
325      format(1X,'Hydrogen Molecular Mass(Exit)=',
&F5.3,4X,'Gamma(Exit)=',F5.3)
      write(1,330)AE,VE
330      format(1X,'Exit Area=',F7.4,' Sq Meters',13X,'Exit
&Velocity=',F9.2,' Meters/sec')
      write(1,340)AMACH
340      format(1X,'Exit-To-Throat Area Ratio= 300',10X,'Exit Mach
&Number= ',F5.2)
*****
* This part of the program uses the method of Masser from Chapter
* 5 to find the constant of integration for the calculation of
* the dose obtained from the plume
*
      f(1)=.07
      f(2)=.00002
      do i=1,2
      BIG=GAMMAE*SQRT(2/(GAMMAE-1)*(2/(GAMMAE+1))**
      &((GAMMAE+1)/(GAMMAE-1)))
      CFCFMAX=(BIG*SQRT(1-(PE/PRES)**((GAMMAE-1)/GAMMAE))+
```

```

&300*PE/PRES)/BIG
X=1/(SQRT(PI)*(1-CFCFMAX))
B=X/4/SQRT(PI)*((GAMMAE-1)/(GAMMAE+1))**.5*(2/(GAMMAE+
&1))**(1/(GAMMAE-1))
TOP=f(i)*QR*6.448E+7*(H2MME*PE/TE/82.06)*AMACH*B*
&AE/PI*10000
BOTTOM=H2DOT*3.7*(1+(GAMMAE-1)/2*AMACH**2)**.5*(2/
&(GAMMAE+1))**((GAMMAE+1)/2/(GAMMAE-1))
CONST=TOP/BOTTOM
350    format(//1X,'lambda=',F15.9,5x,'constant=',f20.4)
        write(1,350)X,CONST
360    format(1X,'f(t)=',f10.7)
        write(1,360)f(i)
        enddo
        close(unit=1)
        stop
        end

```

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PROJECT WISH: THE EMERALD CITY

PHASE II

June 1991

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The purpose of the Permanent Man-made Autonomous Space Oasis, designated Project WISH: The Emerald City, is to serve as permanent living quarters for space colonists. In addition, it will serve as a stopover for space missions and will be capable of resupplying itself practically anywhere within the solar system to support these missions. The station should be self-sufficient, with no specific dependence on any resources from Earth.

The 1990-1991 design team continued work started by last year's class. This year, further studies were conducted in the areas of orbital mechanics, propulsion, attitude control, and human factors. Critical elements were identified in each of these areas, and guidelines were established for the design of the Emerald City. Using the knowledge gained from these studies, two particular missions of interest, a Saturn Envelope mission and an Earth-to-Mars mission, were examined. The size and mass estimates, along with the methodologies used in their determination, are considered to be the main accomplishments of Phase II.

ABSTRACT

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Associate Processor

Hayranı Oz

This report reflects the result of our design classes throughout the second year of Project WISH. The design activity was carried out through a sequence of three courses offered during the autumn, winter, and spring quarters. The autumn quarter course was a technical elective, two credit-hour, introductory course, mainly dedicated to the understanding of the accomplishments of the first phase (1989-1990) of the project and building the background to be able to further the design. The winter quarter course fulfilled a four credit-hour design course requirement for the seniors. During the autumn and winter quarters, seminars by NASA Lewis personnel were included. The spring quarter class was a three credit-hour technical elective course which culminated in this report. Project WISH is measuring up to our expectations in every regard both in technical and educational aspects.

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Subscripts

I - payload
 i - initial, individual
 f - free-flying
 F - final state
 dry - dry (without propellant)
 con - for control
 c - cavity
 atm - atmosphere
 T - total
 RMS - root-mean-square

x - state vector
 t - time, thickness
 r - radius
 n - number of engines, torus spin rate
 m - mass flow rate
 m - mass
 h - height, orbital angular momentum
 g - gravitational constant on surface of Earth, 9.81 m/s^2
 a - acceleration
 Y - inertial reference axis
 X - inertial reference axis
 V - velocity, volume
 TOF - time-of-flight
 R - ratio of thrust to gravity force, major radius of torus
 P - pressure, power
 N - number of crewpeople
 J - impulse
 I - impulse, moment of inertia
 F - force
 D - diameter

Latin

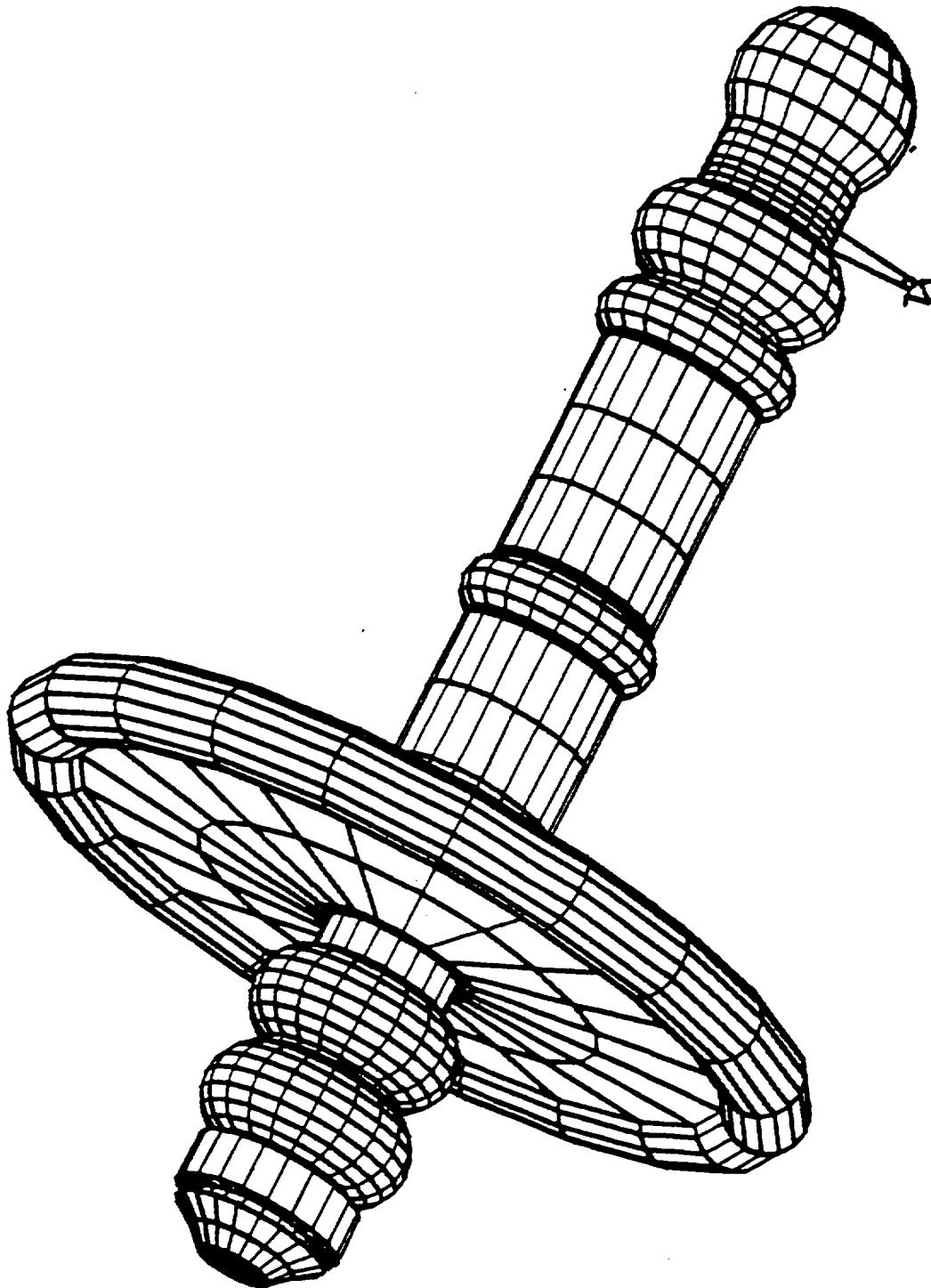
q - orbital angular velocity
 t - period, non-dimensional time
 σ - stress
 ρ - density
 x - 3.141592653
 u - gravitational parameter, $1.3271544 \times 10^{11} \text{ km}^3/\text{s}^2$
 θ - orientation from inertial reference axes
 Δ - change in
 γ - true anomaly
 β - thrust angle

Greek**NOMENCLATURE**

2 - second state
1 - first state
0 - starting state
w - engine
u - uranium
th - thorium
syn - synodic
spe - engine specific
sp - specific
pr2 - second powered flight
pr1 - first powered flight
p - propellant
min - minor
max - maximum

Subscripts (continued)

Figure 1.1 - The Emerald City



precious. Excess amounts of food and supplies have been sacrificed in interplanetary ship carrying the expedition have made cargo space concepts that never fulfilled their potential. Limitations of the finally be either proved conclusively or scrapped with the other of colonizing Titan, which started as far back as the 1990's, will the century. It appears that the speculation about the possibility ever since the Cassini probe first explored it back at the turn of investigate the Saturnian moon Titan, an object of man's curiosity the great ringed planet, Saturn. The purpose of this mission is to The year is now 2060. The first manned mission is arriving at

land of North America.

until the spring and establish a permanent colony in the unexplored the initial months of the settlement, the Pilgrims will survive the support of their ship. With this support, so critical during that endure through the first harsh winter will do so because of across the ocean, for survival. Although some will be lost, those forced to take shelter on the Mayflower, the ship that brought them time to establish themselves firmly on the shore, the Pilgrims are Atlantic Ocean are fighting for their lives. Because there was not pilgrims that have made the journey across the great expanse of the Northeastern coast of the New World. The one hundred and two The year is 1620. Winter has struck with a vengeance on the

1.0 PROJECT OVERVIEW

INTRODUCTION

CHAPTER 1

three year design project currently being conducted at the Ohio Project WISH (Wandering Interplanetary Space Harbor) is a

1.1 PROJECT DESCRIPTION

Introduction of Project WISH.

This discussion of past and future events sets the stage for the this initial support, both missions would be in serious jeopardy. It through the difficult initial stages of their missions. Without dependent upon the support provided by the ships in order to make over 400 years? The success of both of these scenarios is what is the connection between these two events, separated by

ent settlement on Titan.

more confidence, perhaps with the intent of establishing a permanent record, future missions to the moons of Saturn may be made with period of time. With the extra data that could be collected and Emerald City, the mission can remain at Saturn for a much longer their own ship could not address. Because of the presence of the psychological benefits of a large group of people, points which laying that of Earth, providing artificial gravity as well as the desolate vacuum of space. It can also furnish an environment similar to astronauts, as well as a place for them to take refuge from the this historic mission. It will furnish food and equipment for the outside of Saturn's sphere of influence to provide assistance for the of Saturn. Because of this, the Emerald City has taken up station ment needed to thoroughly explore Titan and the other diverse moons to accommodate the extensive scientific and data gathering equipment

lifications of Phase II, and are the focus of this report. The methods used to obtain them, are considered the main accompaniments estimates of the Emerald City for these missions, along with mass estimates of the Saturn Envelope mission and an Earth-to-Mars mission. The size and carry out the design of two particular missions of interest, a design of the Emerald City. These guidelines were then combined to in all of these areas, and guidelines were established for the trade control, and human factors. Critical elements were identified ducted into the disciplines of orbital mechanics, propulsion, attitude control and general study of the major systems required for the Emerald City. During Phase II, a more in-depth study was conducted into the disciplines of orbital mechanics, propulsion, attitude control and human factors. Critical elements were identified during the 1989-1990 academic year, was a general level study of the major systems required for was carried out. Phase I, conducted during the 1990-1991 academic year, was a general level study of the major systems required for the Emerald City. During Phase II of Project WISH century.

During the 1990-1991 academic year, Phase II of Project WISH transportation network throughout the latter half of the 21st a lifetime of fifty years, making it an essential link in the space Emerald City flexible in its mission planning. It also should have periods of three years or less whenever possible, thus making the the solar system. This relocation should be accomplished in city will have the ability to relocate itself virtually anywhere in missions in the solar system. To provide this support, the Emerald inhabitants and to provide crucial support for interplanetary to serve as permanent living quarters for between 500-1000 space Figure 1.1). The purpose of Project WISH and the Emerald City is entity Manned Autonomous Space Oases, designated Emerald City (see State University. This project deals with the design of a Permanent

will be doing throughout the solar system.

In WISH stands for "Wandering", and that is what the Emerald City transfers to as many of the planets as possible. After all, the W chosen. This nominal orbit should yield the most advantageous with the hope that a more substantiated nominal orbit could be rigorous study was performed on the transfers for the Emerald City, the experience gained during last year's design effort, a more asteroid belt than a detailed study of orbital mechanics. Using but this value was selected due more to the proximity of the developed. A preliminary nominal orbit was chosen at 3.2 AU's, understanding of the computer programs used in the investigation was binary mission analysis was conducted in an ad hoc manner as an unsolar system to another in a certain time. Last year, some preliminary for the Emerald City to make a transfer from one place in the andics is used to find the velocity changes, or AV's, that are needed- Emerald City in the gravitational field of the sun. Orbital mech- the context of Project WISH, this deals with the motion of the tational field of a larger body, known as the "central body". In smaller body, broadly termed as the "satellite", in the grav- WISH. In general, orbital mechanics deals with the motion of a WISH. One of the areas studied in-depth during Phase II of Project orbital mechanics is a central discipline in space design, and

2.0 INTRODUCTION

ORBITAL MECHANICS

CHAPTER 2

One of the main goals set down for Project MISH this year was the determination of a nominal orbit in heliocentric space. This nominal orbit would act as a sort of "home base" for the Emerald City, a place where it could return between missions for rest and refit. The original design requirement for the project called for a maximum flight time of three years from this chosen orbit to any planet in the solar system. The idea was to make the Emerald City mobile enough to be able to react to orders requiring its presence at a certain planet within a reasonable time frame. However, it was quickly discovered that this requirement placed an untenable burden on the prospective population systems of the Emerald City, while extrapolating well into the 21st century. Thus the design goals were pared down (increasing the flight times to some planets even extrapolating well into the 21st century. Thus the design make them more attainable for the time frame being considered.

In the selection of the nominal orbit, an attempt was made to keep the flight times to a minimum while retaining as much of the solar system as possible in the "flight envelope". After much discussion, a new set of design goals emerged for the orbital discussion, a new set of design goals emerged for the orbital mechanics and population groups of Project MISH. First of all, it is assumed that the Emerald City will become operational sometime in the mid-21st century. At this time, it is envisioned that humans have become firmly established on the Moon and Mars, and are beginning to look beyond. The next logical step could perhaps be humanizing to look beyond.

2.1.1 Background

2.1 NOMINAL ORBIT

exploration of the asteroid belt and the moons of Jupiter. Using such a scenario as background, all of the planets in the solar system were categorized by their perceived importance to human-kind's exploration of the solar system in the mid-21st century. These categories were employed as a guide in the decision-making process of what the nominal orbit should be and how much thrust the propulsion system of the Emerald City would need to provide.

The first category is made up of the planets considered very important and consists of Earth, Mars, and Jupiter. These planets during the next century. As mentioned earlier, colonies should already be established on the Moon and Mars, and intensive scientific study with preliminary exploration could be taking place on them in three years or less would be essential to provide support to these colonies and/or exploration missions. The second category is planets deemed important and is made up of Venus, Saturn, and Uranus. These are planets that would be targets for scientific study, but are not considered as crucial as the planets in the first category. Thus, it was decided that for these planets, transfers of up to five years would be allowable. The third and final category is planets considered to be of least interest, and includes Mercury, Neptune, and Pluto. While these planets have much to offer in terms of scientific value, it was felt that in the time frame of Project WISH, there would be little need for trips to these planets by a spacecraft like the Emerald City. Thus, the final category is planets considered to be of least interest, and includes Mercury, Neptune, and Pluto. While these planets have much to offer in terms of scientific value, it was felt that in the time frame of Project WISH, there would be little need for trips to these planets by a spacecraft like the Emerald City.

time period. For example, if some crucial product is required for wherever it may be needed in the solar system within a reasonable definition, the Emerald City is to have the capability to travel WISH is the lack of a particular mission to analyze. By The main difficulty in the mission analysis portion of Project

2.1.2 Mission Analyses

analyses was carried out.

the cake. Thus, with the above criteria established, the mission be possible in less than five years would be considered fitting on there were no specific design goals set; any transfers that would reasonable. For the third category (Mercury, Neptune, Pluto), and still keep the population system requirements somewhat should be able to make the transfer as much of the time as possible by not requiring the Emerald City to make the transfer 100% of the time. The design goal would instead be that the Emerald City somewhat by allowing transfers up to five years if necessary, and category (Venus, Saturn, Uranus), these requirements were eased category (Earth, Mars, Jupiter). For the planets in the important requirement was only applied to the planets in the very important nominal orbit to any planet 100% of the time in three years, this instead of requiring the Emerald City to make transfers from the beginning of last year were adjusted to more reasonable levels. By using the above criteria, the design goals given at the planets would lie in a favorable orientation with the Emerald City. only trips made to these planets would be in special cases when the

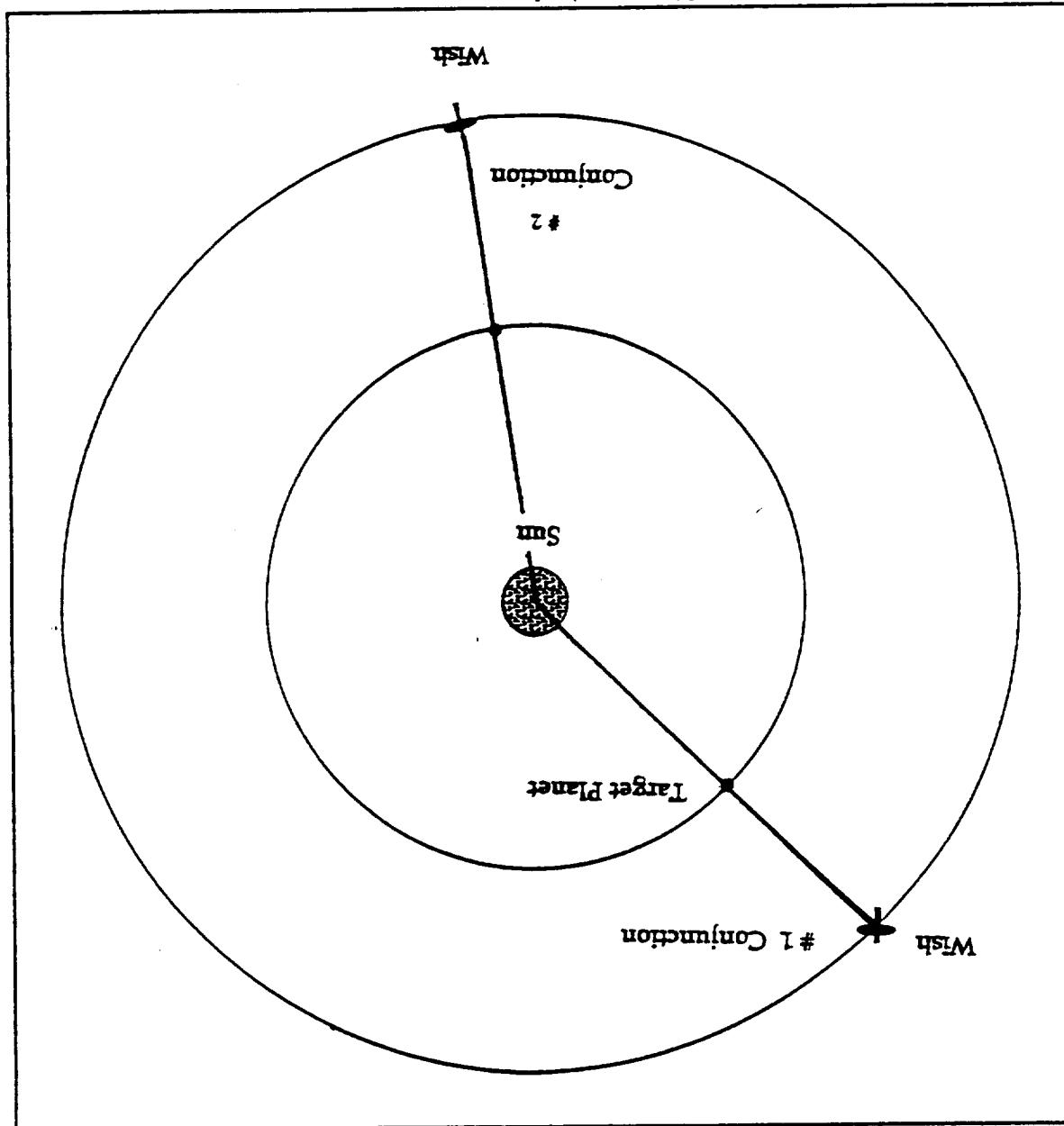
a fledgling colony on a Jovian moon, the Emerald City will not have the luxury of waiting years for the opening of a launch window to Jupiter before leaving the nominal orbit. Instead, it must be able to make the transfer immediately, regardless of where the planet might be with respect to the Emerald City. This so-called "transfer-on-demand" results in high AV's, which is the amount of velocity change that must be provided to the Emerald City in order for it to achieve a transfer from the nominal orbit to a planet. In turn, this high AV places a considerable burden on the propulsion system of Project WISH. Thus, it is hoped to keep these target planets and launch dates for sample cases was discussed, but analysis for the Emerald City. An ad hoc approach of picking a methodology was established that allowed a more thorough investigation of the transfers between a nominal orbit and the planets in the solar system to be performed. This methodology is based on a certain angular orientation known as the phase angle between two bodies to repeat itself. For example, as shown in Figure 2.1, at some time $t = 0$, the Emerald City and the target planet will lie in a straight line connecting the two to the sun. At this point, the concept known as the synodic period is the time it takes for a certain angular orientation known as the phase angle between two bodies to repeat itself (see Figure 2.1). The synodic period is the time it takes for a certain angular orientation known as the phase angle between two bodies to repeat itself (see Figure 2.1).

(see Chapter 3).

Hence, the question arises as to how to perform the mission of the propagation problems associated with large velocity changes of the propagation mission AV's down to reasonable values in order to alleviate some mass loss. As a result, it is hoped to keep these target planets and launch dates for sample cases was discussed, but was ruled out due to its lack of rigor and tedious nature. Instead, a methodology was established that allowed a more thorough investigation of the transfers between a nominal orbit and the planets in the solar system to be performed. This methodology is based on a certain angular orientation known as the phase angle between two bodies to repeat itself (see Figure 2.1).

city and they will once again be in conjunction at some new position at a future time, the target planet will essentially "lap" the Emerald Planet due to the fact that it lies further from the sun. Thus, at however, the Emerald City will be travelling slower than the target planet angle between the two is zero, which is known as conjunction.

Figure 2.1 - The Synodic Period



all of the planets except Mercury and Pluto. Perfect, they are adequate for this preliminary investigation for can be seen from Table 2.1 that, while these assumptions are not but would depend on where the planet is located in its orbit. It invalid, then the AV would not be cyclic with time as was stated,etary orbits all lie in the same plane. If these assumptions were tical, while the second assumption is that the nominal and plan- is that the orbits of the planets are circular instead of ellipti- statement that the AV was cyclic with time. The first assumption assumptions on the geometry of the orbits that were made in the be applied to the transfer at any future time. There are two single synodic period. This will result in values for AV that can city is envisioned to be operating in, they can be examined over a fers throughout the entire fifty year period that the Emerald is given by the synodic period. Thus, instead of looking at trans- of the bodies, it will be nearly cyclic in time, with a period that between two bodies in a given time is a function of the orientation analysis. Because the AV required to make a heliocentric transfer angle to repeat itself, it can be extremely helpful in the mission since the synodic period represents the time it takes for a phase

$$T_{sy} = \frac{2\pi}{Q_{sy}}. \quad (2.1)$$

and Q_{sy} , and is given by period is related to the angular velocities of the two bodies, Q_{sy} called the synodic period, and is denoted by T_{sy} . The synodic tion in their orbits. The time it takes for this to occur is the

follows. First, a nominal orbit radius was chosen and input into trigation. The steps in the mission analysis then proceeded as time to keep this assumption valid for this precursor survey should be sufficiently short with respect to the overall flight hamper the study because the population system powered-flight times i.e., infinite acceleration. Again, this assumption should not assume that the change in velocity takes place instantaneously, relates the AV required for interplanetary transfers under the Project WISH was conducted. MULIMP is a FORTRAN code that calculates periods for a given nominal orbit radius, the mission analysis for Research Center and a simple code written to calculate the synodic using the computer program MULIMP, obtained from NASA Lewis.

Eccentricity = 0 \Rightarrow same orbital plane as Earth

Inclination = 0 \Rightarrow circular orbit

Planet	Eccentricity	Inclination
Mercury	0.21	7.0°
Venus	0.01	3.4°
Earth	0.02	0.0°
Mars	0.09	1.9°
Jupiter	0.05	1.3°
Saturn	0.05	2.5°
Uranus	0.05	0.8°
Neptune	0.01	1.8°
Pluto	0.26	17.1°

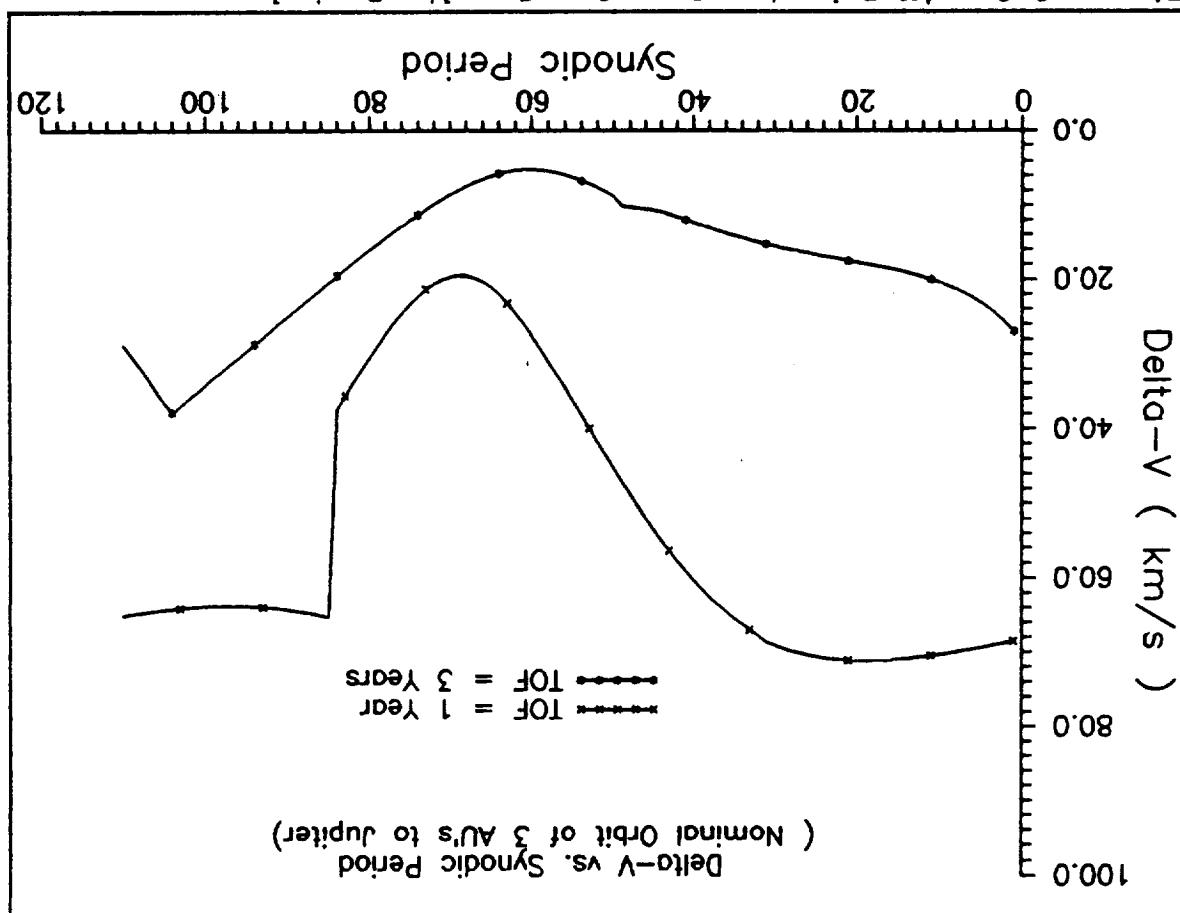
Table 2.1 - Eccentricity and Inclination of the Planets

data obtained from MULIMP, a program was written that would of graphs that had been generated. To aid in the analysis of theious. Then, the question would be what would one do with the pictures the planets at each nominal orbit considered would be quite tedious to plot out and analyze graphs such as figure 2.2 for all of tions.

are so close is a good indication of the validity of the assumption the synodic period does not match exactly, but the fact that they tricity and inclination. Thus, the AV at each of the endpoints of MULIMP uses the actual orbits of the planets, complete with eccentricity while these assumptions were made to facilitate the analysis. While these assumptions that were made about the geometries of the orbits. assumptions that were made about the geometries of the orbits expected. The small difference can be attributed to the two period, the AV is nearly the same as it was at the beginning, as high. It can also be seen that at the completion of one synodic points it is relatively low while at other points, it is quite can be seen how the AV varies over the synodic period; at some nomical units, 1 AU is distance from Earth to Sun) to Jupiter. It graph is for a transfer from a nominal orbit of 3 AU's (astrograps similar to the one shown in figure 2.2. This particular the synodic period that the launch occurred at. This resulted in ship between the AV, the flight time, and the fraction of time into eight times of one to five years in order to obtain the relationship (typically between 100 and 200) over a synodic period and for MULIMP was run for each planet at many different launch dates the code which calculated the synodic periods for this case. Then,

percentage of time during a synodic period that a transfer fails years. The numbers on the right of the chart represent the of 3 AU's to Jupiter (planet #5), with a flight time of three in Table 2.2, N3-P5-T3 would mean a transfer from a nominal orbit transfer was made, and what was the flight time used. For example, chart shows what nominal orbit was used, to what planet the form of a chart, as shown in Table 2.2. The left-hand side of the certain value of AV. Then, this data could be presented in the transfer from a nominal orbit to a planet would fail beneath a calculate the percentage of time during the synodic period that a

Figure 2.2 - AV Behavior Over One Synodic Period
(Flight Time is a Parameter)



Case	AV =	10	20	30	40	50	60	70	80
=====									
N3-P2-T1	0.0	16.5	38.8	56.5	71.4	85.1	97.6	100	100
N3-P2-T2	0.0	9.4	33.3	49.8	64.7	78.0	91.4	100	100
N3-P2-T3	0.0	0.0	26.3	44.3	59.2	73.7	87.5	100	100
N3-P2-T4	0.0	0.0	20.4	40.0	56.0	70.6	84.3	98.8	100
N3-P2-T5	0.0	0.0	18.0	36.0	52.9	67.8	82.4	97.6	100
N3-P3-T1	0.0	25.6	50.2	70.0	85.0	98.2	100	100	100
N3-P3-T2	0.0	28.6	48.0	64.0	78.3	91.6	100	100	100
N3-P3-T3	0.0	18.1	40.5	57.3	72.7	86.8	100	100	100
N3-P3-T4	0.0	8.8	34.8	52.9	68.3	83.7	99.1	100	100
N3-P3-T5	0.0	0.0	31.0	49.3	65.6	81.5	96.9	100	100
N3-P4-T1	0.0	31.5	57.0	85.6	96.3	100	100	100	100
N3-P4-T2	13.7	44.1	60.7	74.1	87.8	100	100	100	100
N3-P4-T3	9.3	43.0	61.9	75.6	86.7	98.5	100	100	100
N3-P4-T4	0.0	28.1	48.9	63.7	78.5	96.7	100	100	100
N3-P4-T5	0.0	29.3	52.6	68.9	81.5	93.7	100	100	100
N3-P5-T1	0.0	7.3	20.9	29.1	34.5	40.9	92.7	100	100
N3-P5-T2	11.8	32.7	83.6	99.1	100	100	100	100	100
N3-P5-T3	24.5	70.0	89.1	99.1	100	100	100	100	100
N3-P5-T4	39.1	70.0	87.3	94.3	100	100	100	100	100
N3-P5-T5	40.9	68.2	84.5	100	100	100	100	100	100
N3-P6-T1	0.0	0.0	0.0	0.0	0.0	18.7	29.0	100	100
N3-P6-T2	0.0	0.0	8.8	34.7	49.2	100	100	100	100
N3-P6-T3	0.0	18.1	45.6	94.3	100	100	100	100	100
N3-P6-T4	0.0	37.8	81.9	100	100	100	100	100	100
N3-P6-T5	11.9	57.0	87.0	100	100	100	100	100	100
N3-P7-T1	0.0	0.0	0.0	0.0	0.0	6.860	OPTIMAL FLIGHT TIME = 6.860	100	100
N3-P7-T2	0.0	0.0	0.0	0.0	0.0	29.9	69.7	100	100
N3-P7-T3	0.0	0.0	0.0	0.0	0.0	27.2	75.2	100	100
N3-P7-T4	0.0	0.0	0.0	35.4	75.2	100	100	100	100
N3-P7-T5	0.0	0.0	0.0	29.9	69.7	100	100	100	100
N3-P8-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N3-P8-T2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N3-P8-T3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N3-P8-T4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N3-P8-T5	0.0	0.0	0.0	0.0	0.0	26.9	54.3	100	100

(Middle Seven Planets, Nominal Orbit = 3 AU)

Table 2.2 - Percentages When Transfer is Possible Given AV Limit

Case AV =	10	20	30	40	50	60	70	80
<hr/>								
N3-P1-T1	0.0	15.1	31.2	45.2	61.3	76.3	90.3	
N3-P1-T2	0.0	0.0	8.6	25.8	39.8	54.8	69.9	86.0
N3-P1-T3	0.0	0.0	3.2	21.5	34.4	50.5	65.6	80.6
N3-P1-T4	0.0	0.0	0.0	18.3	32.3	46.2	62.4	78.5
N3-P1-T5	0.0	0.0	0.0	15.1	29.0	44.1	58.1	76.3
N3-P2-T1	0.0	16.5	38.8	56.5	71.4	85.1	97.6	
N3-P2-T2	0.0	9.4	33.3	49.8	64.7	78.0	91.4	100
N3-P2-T3	0.0	0.0	0.0	26.3	44.3	59.2	73.7	87.5
N3-P2-T4	0.0	0.0	0.0	20.4	40.0	56.1	70.6	84.3
N3-P2-T5	0.0	0.0	0.0	18.0	36.5	52.9	67.8	82.4
N3-P3-T1	0.0	25.6	50.2	70.0	85.0	98.2	100	
N3-P3-T2	0.0	28.6	48.0	64.0	78.0	91.6	100	100
N3-P3-T3	0.0	18.1	40.5	57.3	72.7	86.8	100	100
N3-P3-T4	0.0	8.8	34.8	52.9	68.3	83.7	99.1	100
N3-P3-T5	0.0	0.0	0.0	31.3	49.3	65.6	81.5	96.9
N3-P4-T1	0.0	31.5	57.0	85.6	96.3	100	100	100
N3-P4-T2	13.7	44.1	60.7	74.1	87.8	100	100	100
N3-P4-T3	9.3	43.0	61.9	75.6	86.7	98.5	100	100
N3-P4-T4	0.0	28.1	48.9	63.7	78.5	96.7	100	100
N3-P4-T5	0.0	0.0	0.0	29.3	52.6	68.9	81.5	93.7

Table 2.3 - Percentage Planets When Flight is Possible Given AV Limit
(Inner Planets, Nominal Orbit = 3 AU)

The resulting charts from the mission analysis can be found in tables 2.3-2.10 for nominal orbits of 3, 4, 5, and 10 AU's. These were broken down into the inner planets in tables 2.3-2.6 and the outer planets in tables 2.7-2.10.

2.1.3 Analyses Results

Below a certain AV. By using charts such as the one found in table 2.2, different transfer characteristics can be examined quickly and completely, as opposed to a piecemeal approach, which would be time consuming and not as thorough. Thus, now the merits of different cases can be compared.

Table 2.4 - Percentages When Light is Possible Given AV Limit
 (Inner Planets, Nominal Orbit = 4 AU)

Case AV =	10	20	30	40	50	60	70	80
N4-P1-T1	0.0	0.0	15.2	33.7	51.1	63.0	73.9	
N4-P1-T2	0.0	0.0	27.2	43.5	56.5	66.3	76.1	
N4-P1-T3	0.0	0.0	19.6	39.1	52.2	64.1	73.9	
N4-P1-T4	0.0	0.0	10.9	35.9	48.9	62.0	71.7	
N4-P1-T5	0.0	0.0	0.0	8.7	31.5	46.7	59.8	69.6
N4-P2-T1	0.0	0.0	18.3	41.5	61.0	79.3	95.1	100
N4-P2-T2	0.0	0.0	12.2	35.4	53.7	68.3	82.9	96.3
N4-P2-T3	0.0	0.0	7.3	31.7	51.2	64.6	79.3	93.9
N4-P2-T4	0.0	0.0	0.0	25.6	45.1	59.8	74.4	89.0
N4-P2-T5	0.0	0.0	0.0	19.5	41.5	58.5	74.4	89.0
N4-P3-T1	0.0	0.0	27.1	50.7	75.0	93.6	100	100
N4-P3-T2	0.0	0.0	29.3	50.0	66.4	81.4	95.7	100
N4-P3-T3	0.0	0.0	24.3	45.0	61.0	76.4	91.4	100
N4-P3-T4	0.0	0.0	17.1	40.0	57.1	73.6	87.9	100
N4-P3-T5	0.0	0.0	10.7	36.4	55.0	70.7	85.7	100
N4-P4-T1	0.0	12.4	34.5	60.2	95.6	100	100	100
N4-P4-T2	10.6	41.6	65.5	85.8	100	100	100	100
N4-P4-T3	7.1	40.7	63.7	77.9	95.6	100	100	100
N4-P4-T4	0.0	31.9	54.0	74.3	94.7	100	100	100
N4-P4-T5	0.0	25.7	54.0	73.5	90.3	99.1	100	100

Case AV =	10	20	30	40	50	60	70	80
=====								
N5-P1-T1	0.0	0.0	0.0	8.8	26.4	37.4	53.8	69.2
N5-P1-T2	0.0	0.0	0.0	7.7	23.1	41.8	54.9	69.2
N5-P1-T3	0.0	0.0	0.0	41.2	41.8	54.9	69.2	83.5
N5-P1-T4	0.0	0.0	0.0	22.0	40.7	56.0	68.1	81.3
N5-P1-T5	0.0	0.0	0.0	17.6	37.4	50.5	64.8	78.0
N5-P2-T1	0.0	0.0	0.0	21.7	40.8	62.5	83.3	100
N5-P2-T2	0.0	0.0	0.0	33.3	51.7	68.3	84.2	100
N5-P2-T3	0.0	0.0	0.0	31.7	50.0	66.7	81.7	97.5
N5-P2-T4	0.0	0.0	0.0	26.7	46.7	66.7	81.7	97.5
N5-P2-T5	0.0	0.0	0.0	24.2	44.2	60.8	77.5	93.3
N5-P3-T1	0.0	0.0	0.0	28.9	51.1	78.5	100	100
N5-P3-T2	0.0	0.0	0.0	23.7	46.7	66.7	83.7	99.3
N5-P3-T3	0.0	0.0	0.0	25.9	46.7	65.2	80.7	97.0
N5-P3-T4	0.0	0.0	0.0	21.5	43.0	62.2	77.8	94.1
N5-P3-T5	0.0	0.0	0.0	17.0	40.0	59.3	76.3	91.9
N5-P4-T1	0.0	0.0	0.0	12.2	31.7	52.5	94.2	100
N5-P4-T2	0.0	0.0	0.0	33.8	64.0	84.2	99.3	100
N5-P4-T3	0.4	41.7	64.0	83.5	100	100	100	100
N5-P4-T4	9.4	41.7	64.0	83.5	100	100	100	100
N5-P4-T5	0.0	0.0	0.0	34.5	56.1	76.3	97.1	100

Table 2.5 - Percentages When Light is Possible Given AV Limit
 (Inner Planets, Nominal Orbit = 5 AU)

Case	AV =	10	20	30	40	50	60	70	80
(Inner Planets, Nominal Orbit = 10 AU)									
NLO-P1-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.4	
NLO-P1-T2	0.0	0.0	0.0	4.4	22.2	36.7	51.1	68.9	
NLO-P1-T3	0.0	0.0	5.6	18.9	36.7	53.3	68.9	87.8	
NLO-P1-T4	0.0	0.0	12.1	28.9	43.3	58.9	76.7	93.3	
NLO-P1-T5	0.0	0.0	13.3	30.0	45.6	61.1	77.8	94.4	
NLO-P2-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.2	
NLO-P2-T2	0.0	0.0	0.0	17.2	35.3	56.0	76.7	97.4	
NLO-P2-T3	0.0	0.0	15.5	37.9	57.9	75.8	96.6	100	
NLO-P2-T4	0.0	0.0	27.6	48.3	66.4	84.5	100	100	
NLO-P2-T5	0.0	0.0	31.9	51.7	68.1	85.3	100	100	
NLO-P3-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.7	
NLO-P3-T2	0.0	0.0	0.0	22.0	43.3	68.5	95.3	100	
NLO-P3-T3	0.0	0.0	28.3	50.4	73.2	95.3	100	100	
NLO-P3-T4	0.0	14.2	39.4	62.4	82.1	100	100	100	
NLO-P3-T5	0.0	21.3	44.1	64.6	84.3	100	100	100	
NLO-P4-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.8	
NLO-P4-T2	0.0	0.0	0.0	25.9	52.4	87.1	100	100	
NLO-P4-T3	0.0	0.0	34.7	66.7	94.6	100	100	100	
NLO-P4-T4	0.0	23.8	53.7	79.6	99.3	100	100	100	
NLO-P4-T5	0.0	32.0	59.9	83.7	100	100	100	100	

Table 2.6 - Percentages When Flight is Possible Given AV Limit

Table 2.7 - Percentages When Flight is Possible Given AV Limit
 (Outer Planets, Nominal Orbit = 3 AU)

Case AV = 10 20 30 40 50 60 70 80
=====
N3-P5-T1 0.0 7.3 20.9 29.1 34.5 40.9 92.7 100
N3-P5-T2 11.8 32.7 83.6 99.1 100 100 100 100
N3-P5-T3 24.5 70.0 89.1 100 100 100 100 100
N3-P5-T4 39.1 70.0 87.3 100 100 100 100 100
N3-P5-T5 40.9 68.2 84.5 100 100 100 100 100
N3-P6-T1 0.0 0.0 0.0 0.0 0.0 0.0 18.7 29.0
N3-P6-T2 0.0 0.0 0.0 0.0 0.0 0.0 100 100
N3-P6-T3 0.0 18.1 45.6 94.3 100 100 100 100
N3-P6-T4 0.0 37.8 81.9 100 100 100 100 100
N3-P6-T5 11.9 57.0 87.0 100 100 100 100 100
N3-P7-T1 0.0 0.0 0.0 0.0 0.0 0.0 100 100
N3-P7-T2 0.0 0.0 0.0 0.0 0.0 0.0 100 100
N3-P7-T3 0.0 0.0 0.0 0.0 0.0 0.0 13.8 33.5
N3-P7-T4 0.0 0.0 0.0 0.0 0.0 0.0 100 100
N3-P7-T5 0.0 0.0 0.0 0.0 0.0 0.0 100 100
N3-P8-T1 0.0 0.0 0.0 0.0 0.0 0.0 100 100
N3-P8-T2 0.0 0.0 0.0 0.0 0.0 0.0 100 100
N3-P8-T3 0.0 0.0 0.0 0.0 0.0 0.0 13.0 0.0
N3-P8-T4 0.0 0.0 0.0 0.0 0.0 0.0 42.6 91.9
N3-P8-T5 0.0 0.0 0.0 0.0 0.0 0.0 54.3 100
N3-P9-T1 0.0 0.0 0.0 0.0 0.0 0.0 100 100
N3-P9-T2 0.0 0.0 0.0 0.0 0.0 0.0 100 100
N3-P9-T3 0.0 0.0 0.0 0.0 0.0 0.0 13.7 0.0
N3-P9-T4 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
N3-P9-T5 0.0 0.0 0.0 0.0 0.0 0.0 19.1 40.4

Table 2.8 - Percentages When Flight is Possible Given AV Limit
 (Outer Planets, Nominal Orbit = 4 AU)

	Case AV = 10	20	30	40	50	60	70	80
=====								
N4-P5-T1	0.0	11.0	18.5	24.0	29.5	36.3	43.8	94.5
N4-P5-T2	12.3	28.1	50.7	99.3	100	100	100	100
N4-P5-T3	22.6	78.8	95.9	100	100	100	100	100
N4-P5-T4	46.6	79.5	94.5	100	100	100	100	100
N4-P5-T5	56.8	80.1	93.8	100	100	100	100	100
N4-P6-T1	0.0	0.0	0.0	1.4	16.7	20.8	25.0	
N4-P6-T2	0.0	0.0	20.1	32.6	41.7	98.6	100	100
N4-P6-T3	0.0	22.2	45.1	99.3	100	100	100	100
N4-P6-T4	2.1	38.2	94.4	99.3	100	100	100	100
N4-P6-T5	18.8	67.4	96.5	100	100	100	100	
N4-P7-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N4-P7-T2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N4-P7-T3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N4-P7-T4	0.0	0.0	5.4	36.5	70.9	100	100	
N4-P7-T5	0.0	0.0	31.1	73.0	100	100	100	
N4-P8-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N4-P8-T2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N4-P8-T3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N4-P8-T4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N4-P8-T5	0.0	0.0	0.0	27.9	49.6	100	100	
N4-P9-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N4-P9-T2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N4-P9-T3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N4-P9-T4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N4-P9-T5	0.0	0.0	0.0	0.0	0.0	15.4	41.0	

Table 2.9 - Percentages When Flight is Possible Given AV Limit (Outer Planets, Nominal Orbit = 5 AU)

Case	AV =	10	20	30	40	50	60	70	80
=====									
N10-P5-T1	0.0	0.0	0.0	11.0	14.8	17.4	20.6		
N10-P5-T2	0.0	0.0	20.6	27.1	32.9	41.9	100	100	
N10-P5-T3	0.0	21.3	36.1	67.1	100	100	100	100	
N10-P5-T4	7.7	35.5	94.8	100	100	100	100	100	
N10-P5-T5	17.4	54.2	100	100	100	100	100	100	
N10-P6-T1	5.2	7.0	10.4	13.0	13.9	14.3	17.8		
N10-P6-T2	6.5	11.3	14.8	19.1	22.2	27.8	33.0	41.7	
N10-P6-T3	8.3	20.4	27.0	33.5	44.8	100	100	100	
N10-P6-T4	15.7	27.4	35.2	97.0	100	100	100	100	
N10-P6-T5	19.1	34.3	97.0	100	100	100	100	100	
N10-P7-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N10-P7-T2	0.0	0.0	0.0	0.0	7.8	12.4	15.7	19.0	
N10-P7-T3	0.0	0.0	0.0	15.0	19.6	24.8	30.1	36.6	
N10-P7-T4	0.0	0.0	16.3	22.9	29.4	38.6	100	100	
N10-P7-T5	0.0	10.5	23.5	32.0	87.6	100	100	100	
N10-P8-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N10-P8-T2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N10-P8-T3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N10-P8-T4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N10-P8-T5	0.0	0.0	0.0	16.7	26.2	34.5	47.6	100	
N10-P9-T1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N10-P9-T2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N10-P9-T3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N10-P9-T4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
N10-P9-T5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.9	

Table 2.10 - Percentages When Flight is Possible Given AV Limit
 (Outer Planets, Nominal Orbit = 10 AU)

the luxury of waiting at its nominal orbit for some amount of time in less than three years time. Thus, the Emerald City would have is so short, the Emerald City would pass through the entire period for transfers to these inner planets. Because the synodic period is a key point in determining what AV's will need to be provided one-quarter of a year for Mercury to over two years for Mars. This

	n = 5 AU	.25	.65	1.10	2.26
	n = 4 AU	.25	.67	1.14	2.46
	n = 3 AU	.25	.70	1.24	2.95

t_{syn} (years)

Planet - Mercury Venus Earth Mars

Table 2.11 - Synodic Periods of the Inner Planets

are rather low, as can be seen in Table 2.7. They range from about the first reason is that the synodic period of the inner planets inspection, this conclusion is incorrect due mainly to two reasons. 60 km/s for the design goals to be met." However, upon closer population system will have to provide a one-way AV of greater than of the time in three years for AV's greater than 60 km/s, then the or less, and according to Tables 2.3-2.6, Earth can be reached 100% of planets that had to be reached 100% of the time in three years following. "Well, since planet Earth fell into the first category 2.6, one might be tempted to arrive at a conclusion similar to the After reading the above discussion and examining Tables 2.3-

After receiving its orders to move, until the AV requirements are sufficiently low to make a transfer possible in less than three years and it would still arrive within three years of the time it received its orders to go somewhere.

For example, say that the Emerald City is in a nominal orbit at 4 AU's from the sun. On February 10, 2051, it receives orders to travel to Earth, and its arrival is required within two years. On February 10, the AV required to make a two year transfer at this time is found to be 63.9 km/s, a rather high value that would place a large burden on the propulsion system. So instead, the Emerald City decides to wait at the nominal orbit until July 3, 2051, when days ahead of the time it was required to be there. This scenario, calculated using MULIMP, is possible because the synodic period for Earth is only 1.14 years, short enough to allow all of the possible phase angles to present themselves to the Emerald City within the time that it is required for it to make the transfer. Thus, instead of leaving immediately, it can wait for some length of time, and then make a transfer that, even with a shorter flight time, has a lower AV because of a more favorable orientation.

The second reason that the percentages that a transfer is possible for a given flight time cannot be taken at face value is because of the following fact. In this analysis, the flight time for each transfer is specified, and the AV required to make this transfer is

sufficiently low to make a transfer possible in less than three years after receiving its orders to move, until the AV requirements are

all of the phase angles between it and the Emerald City will have 100% of the time. Again using the Earth example, in 1.14 years, synodic period for this flight time, then the transfer can be made the synodic period. If a transfer can be made at any point in the transfer can be made at all with a flight time of three years minus meanings. Instead, what should be looked at is the lowest AV a time that a flight is possible for a given AV is rendered planets for the two reasons cited above, the actual percentages of thus, because of the nature of the transfers to the inner much better result.

the transfer in only 2.33 years, the AV would only be 18.8 km/s, a 2.5 years, the AV required would be 46.1 km/s. However, by making Emerald City were to try to make a transfer with a flight time of ordered to be there within 2.5 years. At this point, if the receives orders to proceed to Venus on February 27, 2050, and is in the following example, predicted by MULIM. The Emerald City flight time to be the specified value. This phenomenon can be seen planet, but will still by taking an indirect route in order for the this is because the trajectory will not go directly to the target planets in, say, three years, the AV required actually increases. of one to two years. Thus, by forcing a trip to one of these resulting in the lowest AV) for the inner planets is on the order the inner planets. The optimal flight time (the flight time demanding duration. In general, however, this is not the case for down as the flight time is made longer, because of the less exact transfer is found. One might expect that this AV would go

different nominal orbits can be measured by. It is possible for a fixed AV becomes important, a yardstick that thus, for the outer planets, the percentage of time that a transfer must be prepared to make transfers at less than optimum conditions. Will encounter only a fraction of the possible phase angles, and

$n = 5 \text{ AU}$	196.66	18.02	12.91	12.00	11.71
$n = 4 \text{ AU}$	24.62	10.98	8.85	8.41	8.27
$n = 3 \text{ AU}$	9.26	6.31	5.54	5.37	5.31

t_{syn} (years)

Planet - Jupiter Saturn Uranus Neptune Pluto

Table 2.12 - Synodic Periods of the Outer Planets

Planets, as seen in Table 2.12. Because of this, the Emerald City planets because the synodic periods are much longer for the outer planets than to the inner orbits of 3, 4, 5, and 10 AU's. The investigation of the transfers (Jupiter to Pluto) can be found in Tables 2.7-2.10 for nominal orbits to the outer planets must be treated differently than to the inner

The results from the mission analysis for the outer planets can be reached any percent of the synodic period. Thus, if Earth occurs due to the length of the synodic period. Thus, it can wait until the favorable orientation appears. It can wait until the favorable orientation appears. Of the time in under three years from receiving its orders, because a given AV, then it can be said that the transfer can be made 100% can be reached any percent of the time in 1.86 years or less with

Outer Planets

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discussion of the inner planets previously. Saturn can be reached years or less, considering the points that were brought up in the Venus, Earth and Mars can be reached under AV's of 40 km/s in three would have to provide at least this much AV capability. Also, the beginning of this chapter are to be met, the propulsion system one-way AV of 40 km/s. Thus, if the goals that were laid down at transfer to Jupiter can be accomplished 100% of the time with a 21st century, Mars and Jupiter. From this orbit, a three-year presumed focal points of interplanetary space activity in the mid-deposits of valuable materials can be found, and close to the the Emerald City relatively near to the asteroid belt, where vast between Mars, at 1.5 AU and Jupiter, at 5.2 AU. This orbit puts factors. The first one is the central location of this orbit preliminary nominal orbit. This selection was based on several MUIMP and some discussion, an orbit at 4 AU's was selected as the and 10 AU's. After examining the percentage tables generated by The sample nominal orbits that were examined were at 3, 4, 5,

2.1.4 Nominal Orbit Selection

orbit.

was an important consideration for the selection of the nominal sun, and in some cases, the percentages actually went down. This little benefit gained by moving the nominal orbit away from the reach the outer planets. As seen in Tables 2.7-2.10, there was further from the sun had on the ability of the Emerald City to It should be noted what effect moving the nominal orbit

An interesting point that should be brought up when discussing generally negligible). The necessary AV that the propulsion system must provide is the return to the nominal orbit. Early in this study, it was generally assumed that accounting for the return trip would roughly double the maximum AV that would be necessary. However, upon further investigation, some doubts were raised as to the validity of this assumption. When using the MULIMP code, the orbit of the Emerald city is entered by using the six classical orbital elements; the eccentricity, the semi-major axis, the inclination, the longitude of the ascending node, the argument of the perihelion, and the time of the ascending node, the argument of the perihelion, and the time

nearly 100% of the time at 40 km/s using flight times of three years, which is an added bonus. To reach Uranus with a AV of 40 km/s, flight times of four and five years must be used, and, for five years, the transfer is possible only 73% of the time. This was felt to be unacceptable, because Uranus fell into the category of planets deemed marginally important for exploration in the mid-21st century. Mercury can be reached 100% of the time if a trip to that planet is required, but Neptune and Pluto cannot be reached at all by transfers with flight times up to five years and a AV limit of 40 km/s. Thus, trips to these outer planets would require special considerations, such as somehow refueling part of the way there or increasing the population capabilities. A nominal orbit of 4 AU's also puts the Emerald City within reasonable distance of Earth for communications and emergencies, which is why a larger radius orbit was not selected (the benefits gained by moving the orbit out were

of periapsis passage. For the circular orbits that were examined, there is no periapsis, and the last element is replaced by some value that locates the Emerald City in the orbit at a given time. When going from the nominal orbit to a target planet, the Emerald City will leave from a particular point on the nominal orbit and arrive at the target planet, and the AV can be calculated by MULIMP. However, for the return trip, there is nothing that says the Emerald City has to return to a particular point on the nominal orbit. Instead, it is free to return to any point along the orbit. Unfortunately, when the orbital elements are used to define the nominal orbit, a "ghost point" is created that moves around the defined nominal orbit, as if it were a planet in that "ghost point's" location instead of anywhere on that orbit. Because of this freedom, the Emerald City could return to the transfer, and the AV's would probably not be as high as originally calculated, the AV for a situation like this, so an total AV of 50 km/s was assumed as the necessary upper limit to give to the population system. For the inner planets, this figure should be quite adequate due to the Emerald City's ability to make optimal transfers as was discussed above. For the outer planets, it was felt that this figure should result in 100% ability to reach Jupiter and Saturn in three years and above 50% to reach Uranus in

to be evaluated analytically or by finite-difference methods, etc. . . is linear or non-linear, whether the gradients of the functions are nature of the problem; the type of constraints, whether the problem in the above form. The particular method selected depends upon the much theory developed on techniques to solve optimization problems the range of values that these variables can take. There has been of constraint is on the design variables themselves and specifies the second type is called inequality constraints. The third type constraints, the first type being called equality constraints while variable vector of length n , i.e. n design variables. There are m the function $f(x)$ is the objective function and x is the design

$$x_1 < x < x_n.$$

$$g_j(x) > 0 \text{ for } j = m+1, \dots, m$$

$$g_j(x) = 0 \text{ for } j = 1, \dots, m$$

subject to the constraints

$$\min_{\mathbf{x} \in \mathcal{X}} f(\mathbf{x}) \quad (2.2)$$

The field of optimization is a powerful tool in the engineering design process. The basic optimization problem is one of determining the minimum or maximum a function, called its variables. This problem is represented by objective function, can obtain, subject to certain constraints on the function, can obtain, subject to certain constraints on its variables. This problem is represented by

2.2.1 Introduction

2.2 AV MINIMIZATION

Five years (or less, in some cases). Of course, Neptune and Pluto still are unreachable without some special considerations.

All of these factors will need to be considered when selecting the computer code to be used to solve the optimization problem. With the above discussion in mind, an optimization problem studied this year will be discussed, namely the problem of AV minimization. One of the major problems that has surfaced in the first two years of development of Project WISH deals with the transfers from a nominal orbit to the planets in the solar system. It has been noted that the AV needed for these transfers have a great impact on the propulsion system requirements. As the values for the AV increase, the demands on the propulsion system become considerable. Besides training the propulsion system, this has a cascade effect on the rest of the systems of the Emerald City; greater propulsion system requirements (thrusters, powered-flight times...) lead to more difficult problems in shielding, structural dynamics, propellant storage, etc... Thus, it is in the best interest of the Emerald City to keep these AV's as low as possible. For this reason, it was felt that an optimization of AV was justified in order to keep the population system requirements as reasonable as possible. It may seem that this would be redundant with the work that was presented earlier in this chapter. However, the analysis presented here used a computer program that assumed an instantaneous change in velocity, with no regard for the powered-flight times, thrust required, or the thrust angles that could be used. By performing

2.2.2 Background

With the above discussion in mind, an optimization problem will be solved to solve the optimization problem. All of these factors will need to be considered when selecting the computer code to be used to solve the optimization problem. With the above discussion in mind, an optimization problem studied this year will be discussed, namely the problem of AV minimization.

The third, and most pivotal, assumption is that the trajectory during the powered-flight times is unaffected by the pull of the sun's gravity (see Figure 2.3). During the powered-flight times, the Emerald City is assumed to follow a projectile-like course, during the powered-flight times.

The second powered-flight phase.

This assumption, the acceleration at the end of the first powered-flight phase was set equal to the acceleration at the beginning of this assumption, it was ignorable for this preliminary study. By making would still be applicable for this preliminary study. The validity of this assumption is questionable, but it was reasoned that the results simplicity, it was ignored for this analysis. The validity of this hydrogen due to heat leakage through the storage tanks, but for transfer. Of course, there will be some boil-off of the liquid there is no loss of propellant during the free-flight phase of the interest in Project WISH. The second assumption made was that of the planets except Mercury and Pluto, which are of the least As was shown in Table 2.1, this is a reasonable assumption for all are all in the ecliptic plane, i.e. the same plane as the Earth. The first assumption is that planets are all in circular orbits and regarding the nature of the orbits and transfers had to be made. In order to carry out the optimization, certain assumptions

2.2.3 Assumptions

that will yield the lowest AV. City and the target orbit, typically near the destination planet, account, as well as determining the orientation between the Emerald City's optimization, it is hoped that these factors can be taken into

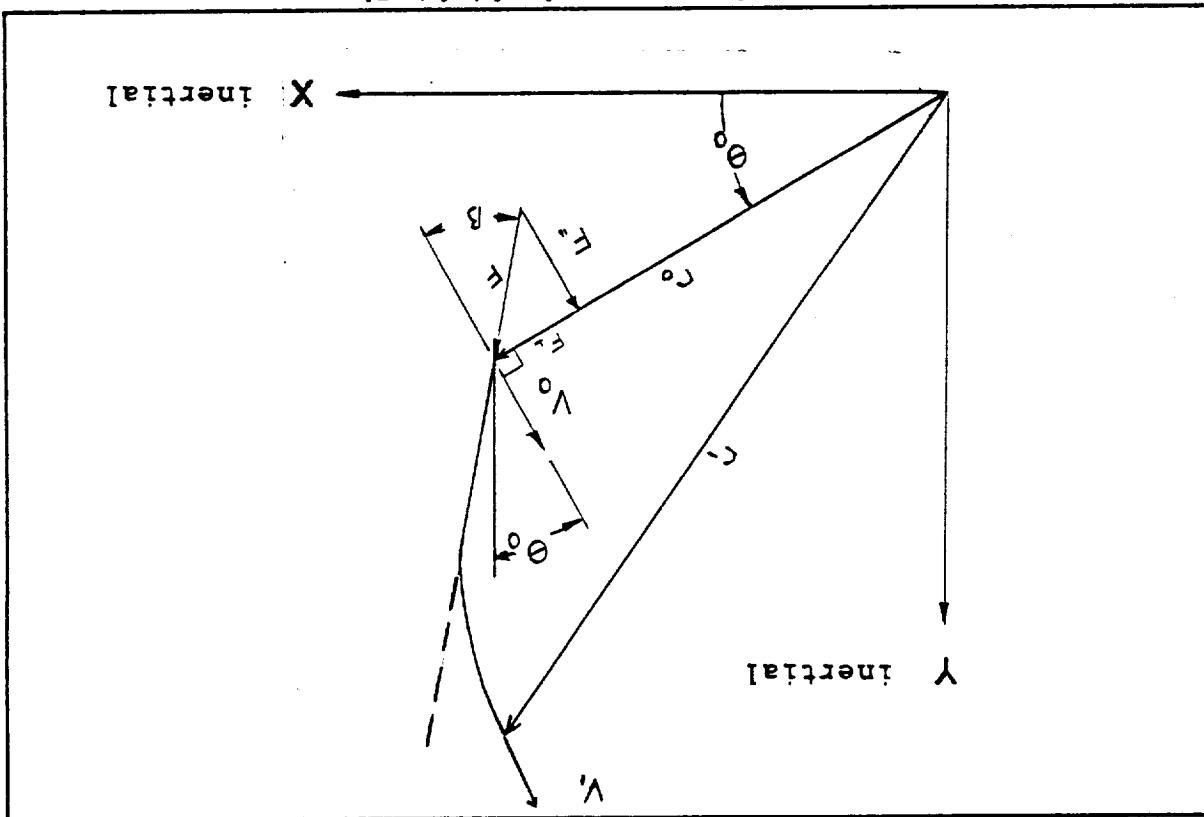
that this assumption was valid for this preliminary investigation. Emerald City, R will be a very large number, and thus it was felt $r(t)$, and ship mass, $m(t)$. For representative values for the $r(t)$, and ship mass, $m(t)$. It can be seen that R is dependent upon the thrust, F_{th} , the radius,

$$m(t) = m_0 - m_f \quad R = 1.327 \times 10^{11} \frac{km^3}{s^2} \quad (2.3)$$

$$R(t) = \frac{a_g}{a_{th}} = \frac{F_{th} t}{\mu m(t)^2}$$

during the powered-flight phases, given by value of the ratio of accelerations due to thrust and gravity acceleration (thrust) vectors. This assumption is based on the determined by the X- and Y-components of the initial velocity and

Figure 2.3 - Assumption for Powered-Flight Phases



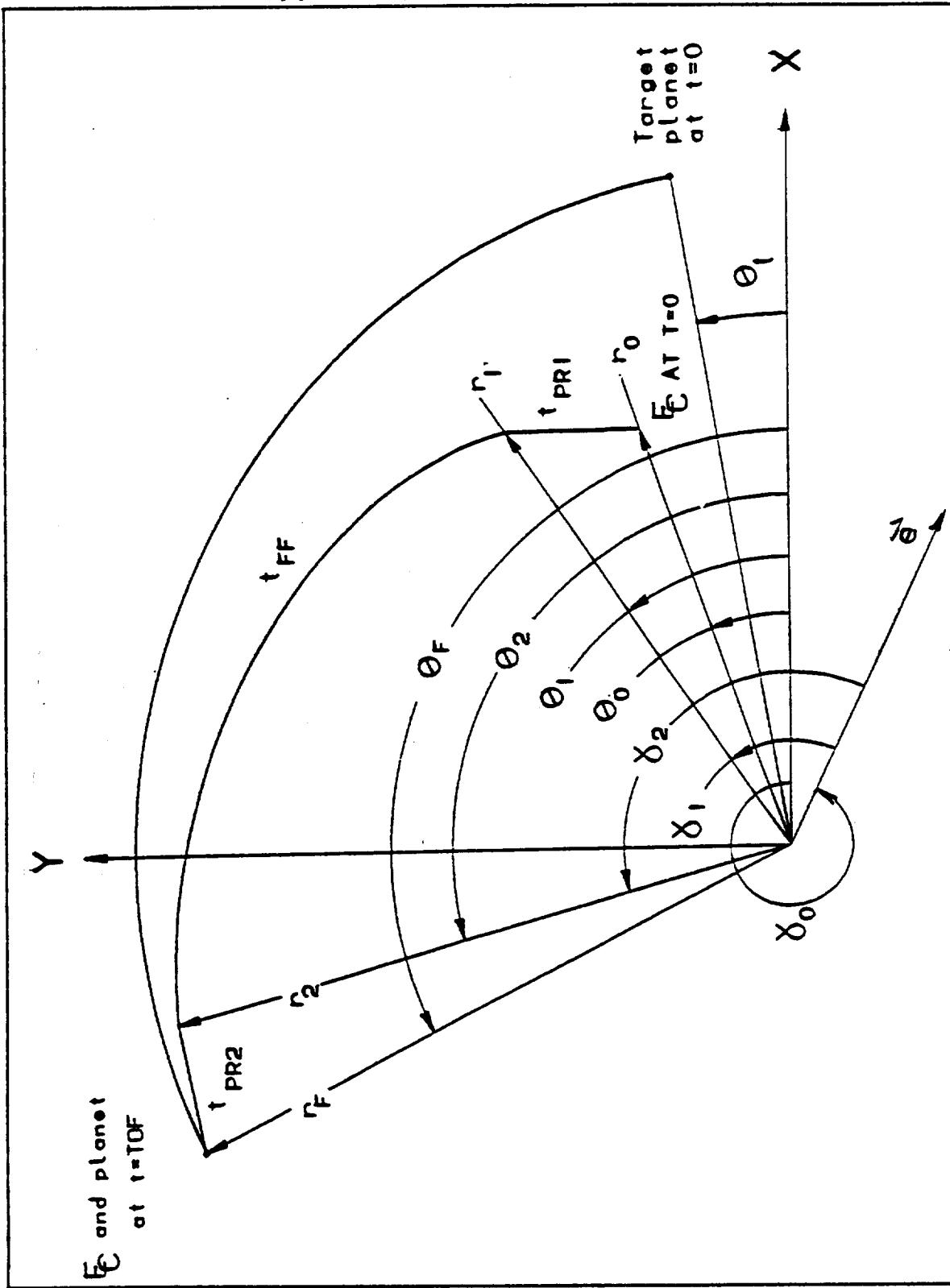
r_0 - nominal orbit radius	defined in Table 2.13.
r_1 - radius at end of first powered-fliight	beginning of second powered-fliight
r_2 - radius at end of free-fliight	beginning of free-fliight
r_f - target orbit radius	target orbit radius
θ_0 - angle between inertial reference frame X-axes and r_0 vector	angle between inertial reference frame X-axes and r_1 vector
θ_1 - angle between inertial reference frame X-axes and r_1 vector	angle between inertial reference frame X-axes and r_2 vector
θ_2 - angle between inertial reference frame X-axes and r_2 vector	angle between inertial reference frame X-axes and r_f vector
θ_i - angle between inertial reference frame X-axes and target planet at launch	angle between inertial reference frame X-axes and target planet at launch
γ_0 - angle between inertial reference frame X-axes and eccentricity vector (line of apsides)	true anomaly of free-fliight orbit at point 1
γ_1 - true anomaly of free-fliight orbit at point 2	true anomaly of free-fliight orbit at

Table 2.13 - Definition of Variables Used in AV Minimization Problem

The geometry that was used for the AV optimization is shown in Figure 2.4. The technique used to model the interplanetary transfer was to break down the transfer into three arcs. The first and last arcs represents the initial and terminal powered-fliight phases, respectively, while the middle arc represents the free-fliight phase. In the powered-fliight portions, the thrust level, powered-fliight times, and thrust angles govern the trajectory, while in the free-fliight portion, the classical relationships governing orbitting bodies are used (more on these relationships can be found in Appendix A). The variables shown in Figure 2.4 are defined in Table 2.13.

2.2.4 Geometry

Figure 2.4 - Geometry for Optimization Problem



$$x_i - \{v_i^e, v_i^f\} \quad (2.5)$$

Point i , x_i , such that

The first step that was taken was to define a state vector for determine equations for the constraints listed above.

that relate v_0 , v_1 , v_f to the design variables chosen and negative magnitudes. Thus the problem is to find the equations physically meaningful solutions found, such as negative times or that time, and the final constraint is to ensure that there are no and velocity of the target orbit near the destination planet at of the Emerald City at the end of the transfer matches the position the rendezvous constraint requires that the position and velocity flight constraint governs the allowable time to make the transfer. limitations of the propulsion system, while the total time-of-acceleration and powered-flight-time constraints arise from the rendezvous requirements, and physical variable constraints. the acceleration levels, the powered-flight time lengths, the problem are given by constraints on the total time-of-flight, the respectively (see Figure 2.4). The general constraints for this where v_1 , v_0 , v_f , and v_e are the velocities at points 1 , 0 , f , and

$$\Delta v_e = \Delta v_1 + \Delta v_0 - (v_e^e - v_1^e) + (v_e^f - v_0^f) \quad (2.4)$$

In an optimization problem, there is a objective function that represents the variable to be optimized and constraint functions that represent the restrictions on the problem. For the Δv minimization problem, the general objective function is

2.2.5 Methodology

$$\Delta V_t = -I_{spg}^2 \ln(1 - \frac{a_0 t_{px2}}{I_{spg}}) + \ln(1 - \frac{I_{spg} - a_0 t_{px1}}{a_0 t_{px2}}), \quad (2.9)$$

After applying equations for ΔV_1 and ΔV_2 as found in Appendix A, the objective function was written as

where the vertical bar signifies dependence on a previous state.

$$\begin{aligned} \dot{x}_2 - x_2(y_2) |_{\bar{x}} + \Delta \dot{x}_2(y_2, a_0, t_{px1}, t_{px2}) \\ \dot{x}_1 - x_1(\theta_0) + \Delta \dot{x}_1(\theta_0, a_0, t_{px1}) \end{aligned} \quad (2.8)$$

and the state vectors were found to be

respectively. The functional dependences between these variables orientations of the Emerald City and the target planet, θ_0 and θ_1 , a_0 , the true anomaly at the end of free-fight, y_2 , and the initial t_{px1} , the two thrust angles, β_1 and β_2 , the acceleration level, and t_{px2} , the two powered-fight times, t_{px1} identified. These variables are the two powered-fight times, t_{px1} and t_{px2} , the nature of the problem, eight design variables were platting the city during the powered and free-fight phases, and by contem-

By examining the equations governing the trajectory of the Emerald City during the powered and free-fight phases, and by comparing the values at the beginning of each powered-fight phase by

$$\Delta \dot{x}_f - \{\Delta \dot{x}_1, \Delta \dot{x}_2\}. \quad (2.7)$$

where

$$\begin{aligned} \dot{x}_f - x_2 + \Delta \dot{x}_2 \\ \dot{x}_1 - x_1 + \Delta \dot{x}_1 \end{aligned} \quad (2.6)$$

The values at the end of each powered-fight phase can be related to the values at the beginning of each powered-fight phase by

effort and some meaningful results obtained.

optimization problem can be programmed during next year's design algorithm and finite difference gradients. It is hoped that this optimization problem using a successive quadratic programming programme. This subroutine solves a general, non-linear problem. A potential optimization subroutine was not due to time and personnel constraints, the problem was not determined, an optimization code can be utilized to solve this problem. Once the objective function and constraint functions are detailed in Appendix A.

free-flying phases of the trajectory. These equations can be found design variables through the equations governing the powered and flight and the rendezvous requirement incorporate the rest of the fourth constraints above. These constraints on the total time-of-five design variables enter into the problem through the first and of the eight design variables, namely a_0 , t_{PL} , and t_{PR} . The other it turns out that the objective function is dependent only on three a_0 , t_{PL} , t_{PR} , $t_{FF} > 0$.

$$4. x_{FF,EC}^t = x_{FF,TO}^t.$$

$$3. t_{PL} + t_{PR} < t_{PL,max}$$

$$2. a_0 < a_{0,max}$$

$$1. t_{FF} + t_{PL} + t_{PR} < t_{OF,max}$$

where I_{sp} is the specific impulse of the propulsion system (see Chapter 3), and g is the gravity constant on the surface of the Earth, 9.81 m/s^2 . The constraint functions may then be written as

This year, a detailed study was performed on the orbital mechanics of Project WISH. Based on this study, a nominal orbit of 600,000,000 kilometers from the sun, between the orbits of Mars and Jupiter. From this orbit, it was determined that the planets Mercury, Venus, Earth, Mars, Jupiter, and Saturn can be reached with this AV in flight times of three years or less with a AV limit of 40 km/s one-way. Uranus can be reached 73% of the time with this AV in flight times of five years, which was felt to be believed that there would be little need for a ship such as the Emerald City to make trips to these planets during the same period of time in flight times of up to five years, but it was all at this AV with flight times of up to five years, but it was considered that the AV minimization problem was also examined and mean-ingful results can be obtained. Also, more work should be done on determining the AV's required to return to the nominal orbit from a planet. With additional study in this area, a more accurate round-trip figure for the AV's can hopefully be obtained. As of the end of this study, a total round-trip AV of 50 km/s was used as the upper ceiling for the Emerald City.

2.3 CONCLUSIONS

The population system of the Emerald City plays an important role in the success of Project WISH. For this reason, it was one of the most rigorous study systems this year. At the conclusion of Phase I design conducted last year, an antimatter engine was selected as the main population system of the Emerald City. However, it was decided during Phase II that antimatter was too theoretical for the time frame of Project WISH, and that the population system chosen should be more readily procurable by the mid-21st century. With the hope of bringing the choice of the population system into the Emerald City's time frame, the population team looked at several areas of interest in spacecraft population system. First, a general level study was conducted in order to determine some of the important parameters associated with population. First, a general level study was conducted in order to determine the significant characteristics of this system. From this study, it was possible to calculate other important parameters that were dependent upon the choice of a particular population system. Finally, this population system was used in the design of two representative missions, which may be found in Chapter 6.

3.0 INTRODUCTION

POPULATION

CHAPTER 3

of generating a high I_{sp} should be utilized. mass required for a given mission down, a propulsion system capable increased or the AV is decreased. Thus, to keep the propellant ship mass consisting of propellant, decreases as the I_{sp} is propellant mass ratio, which is the fraction of the total initial propellant which is plotted in Figure 3.1. This figure demonstrates how the

$$\frac{m}{m_p} = 1 - e^{-\frac{I_{sp}}{AV}} \quad (3.1)$$

by

important role in the equation for the propellant mass ratio, given propellant required to accomplish a mission. The I_{sp} plays an propellant expended, is desirable because it corresponds to less impulsive, which is the impulse produced per unit weight of impulsive levels, i.e., at high specific impulses, I_{sp} . High specific spaccraft, the propulsion system will be required to produce high parameters. Since the Emerald City is expected to be a large mine the effects that the mission requirements have on propulsion this investigation. The first step in the analysis was to determine the physical nature of spacecraft propulsion enters into WISH; only the physical nature of spacecraft propulsion enters into independent of the type of engine that will be used for Project to be for an application such as Project WISH. The study is system, and what the orders of magnitude of these parameters need which parameters play a major role in the choice of a propulsion system purpose of this general level study is to determine

3.1.1 Theoretical Background

3.1 GENERAL PROPULSION STUDY

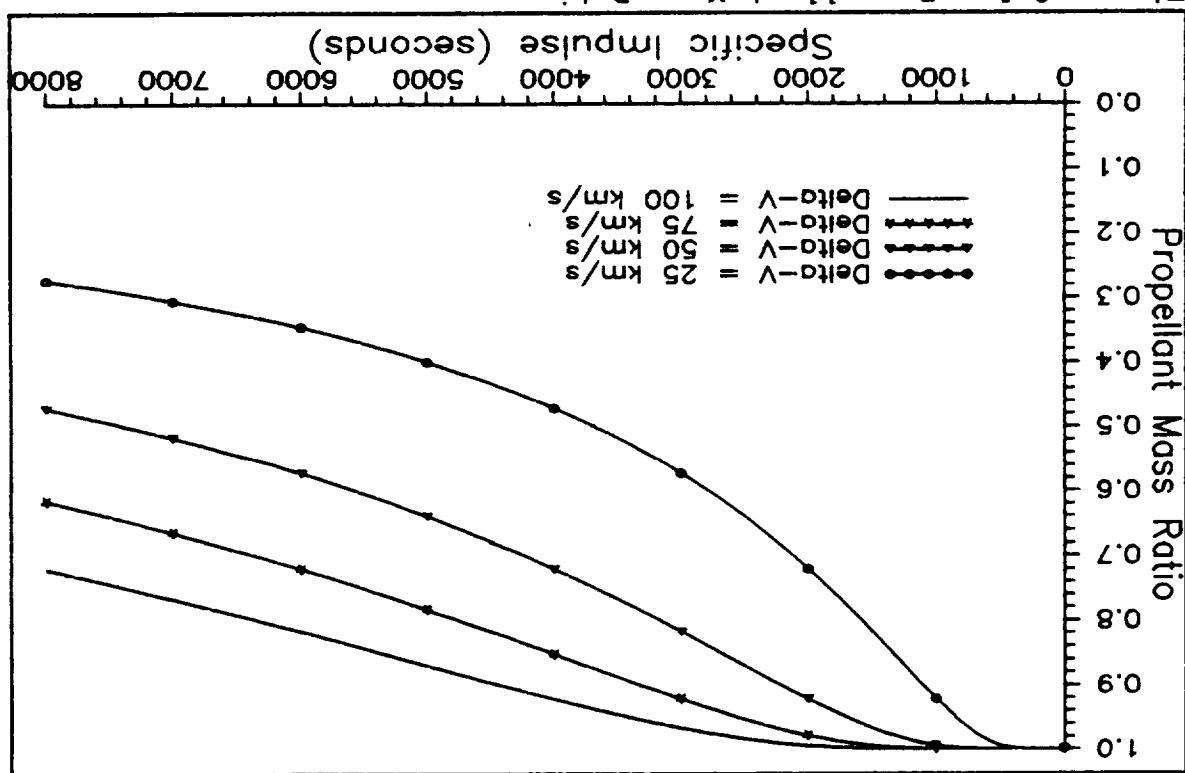
levels that will be required for its missions (see Chapter 2). The factors; the large dry mass of the Emerald City, and the high AV large, on the order of 10^{13} to 10^{14} newtons. This is due to two that the impulse required for an Emerald City mission will be very which is plotted in Figure 3.2. From this figure, it can be seen

$$J = m_{dry} I_{sp} g \left(e^{\frac{AV}{I_{sp} g}} - 1 \right) \quad (3.2)$$

the AV and is given by

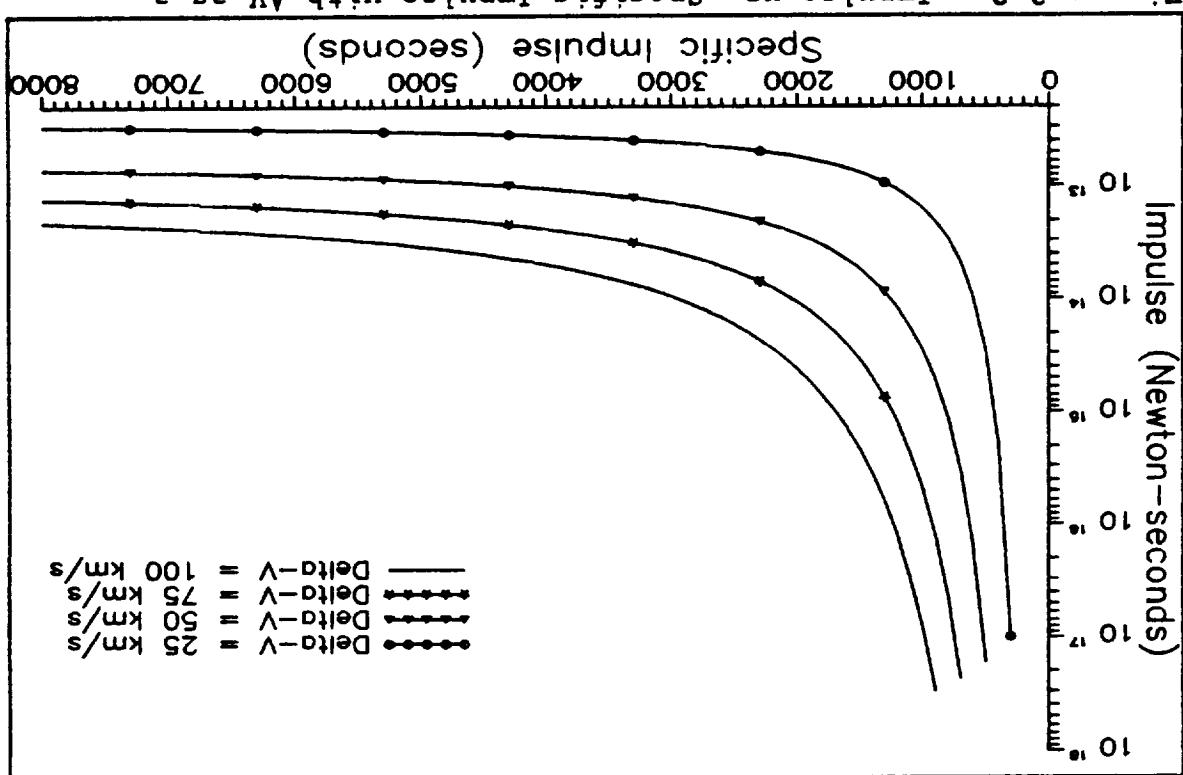
a function of the dry mass of the ship (no propellant included) and as the high I_{sp} 's is needed. The impulse required for a mission is enough. An engine capable of producing high impulse levels as well however, for the Emerald City, a high- I_{sp} engine alone is not

Figure 3.1 - Propellant Mass Ratio vs.
 I_{sp} With AV as a Parameter



required would still be on the order of 10^5 newtons. time (" 3 years or " 10^8 seconds), the thrust that would be 3.2 that, if the Emerald City were to burn for its entire flight maintenance/lifetime viewpoint. It may also be seen from Figure times, t_f . Neither of these are desirable from an engine impulses would necessitate high thrusts, F , and high powered-light to move. Since impulse is the product of a force and a time, high lower I_{sp} 's, which makes the Emerald City heavier and more difficult is because of the extra propellant mass that must be carried at the up, eventually approaching infinity as I_{sp} approaches zero. This from Figure 3.2. As the I_{sp} goes down, the impulse required goes effect that the I_{sp} has on the impulse required can also be seen

Figure 3.2 - Impulse vs. Specific Impulse with ΔV as a parameter and $m_f = 10^6$ kg



group decided that fusion, like antimatter, would be too systems was the question of fission or fusion. The propulsion system for the main points considered when examining nuclear propulsion system for the Emerald City.

Project WISH. Thus, NTP was examined in more detail as a primary combination of high thrust and high I_{sp} that would be required for the nuclear propulsion systems of the 21st century gave the best pulsed (NTP) was the final type of system examined. Estimates of amount of thrust that could be produced. Nuclear thermal production (NTP) produced high enough I_{sp} 's, but were severely limited in the trical propulsion was the next system that was studied. These requirements that the Emerald City would place on them. Electrical requirements, the specific impulses of these systems fell far short of adequate, the specific impulses of these systems were rejected. Although the thrust values were and was promptly rejected. Once it has been determined that high I_{sp} 's and high thrusts

3.1.2 General Propulsion Systems

impulse and thrust levels that each system could provided. The remaining systems were analyzed in terms of the specific nature, even for an advanced project such as Project WISH. Thus, antimatter had already been ruled out for being too theoretical included chemical, electrical, nuclear, and antimatter. However, conducted in an attempt to find such a system from choices that could satisfy these requirements. A general level study was are needed, the next step was to search for a propulsion system once it has been determined that high I_{sp} 's and high thrusts

testing during the NERVA (Nuclear Energy Rocket Vehicle Application) is limited by material availability. Current estimates and some achievable I_{sp} is limited by material considerations, and thus the is limited in temperature by material considerations, and thus the expelled through a convergent-divergent nozzle. However, the core to a light-weight propellant, usually hydrogen, which is then of uranium to generate thermal energy. This energy is transferred suggests, a solid-core NTP system utilizes a fissile solid-core subgroups; solid-core reactors and gas-core reactors. As its name Within the fissile category of NTP, there are two major

Emerald City.

propulsion system would be used for the Phase II design of the fissile reactors in mind, it was decided that a fissile nuclear considerations in mind, it was decided that a fissile nuclear higher I_{sp} 's are still conceptual in nature. With all of these I_{sp} 's for this project, and the more advanced engines with the the more developed types of fissile systems have relatively low an increase in the shielding mass required for human safety. Also, fissile is a rather troublesome radiation problem, which leads to than their fusion counterparts. Unfortunately, associated with the advantage of being more advanced and currently less massive was rejected as a main propulsion candidate. Fission systems have fusion system suitable for the Emerald City, but for now, fusion fusion research could lead to the development of an operational to be substantially more massive. Of course, a breakthrough in compared to the fission systems, the fusion systems are estimated population is the mass penalty that would accompany the system. theoretical for the Emerald City. Another drawback of using fusion

parameters for the two systems considered. This table shows that engine, m¹. Table 3.1 shows some comparison figures of these three investigated, the I^{sp}, the thrust per engine, F₁, and the mass per best for the Emerald City, three main engine parameters were the core. In determining which of these propulsion systems was for better heat transfer, but also leads to a loss of uranium from engine has the propellant and core in direct contact, which allows the propellant and core physically apart. The open-cycle gas-core from the fissile core to heat the propellant while keeping gaseous core encased in a transparent material that allows radiogaseous core (open-cycle, SRGCR). The closed-cycle gas-core engine has its studied, the light bulb (closed-cycle, LRGCR) and space radiator. There were two major types of gas-core nuclear rockets (GCNR) Emerald City.

chosen for further study as the main propulsion system of the system, with its higher estimable thrusters and I^{sp}'s was Project WISH (see Figures 3.1 and 3.2) and thus the gas-core NTP I^{sp} of the solid-core rockets were simply too low for the needs of engine on the order of 2000-8000 seconds. It was felt that the current theoretical studies give a possible I^{sp} for this conceptual model to the propellant, which results in a higher possible I^{sp}. Increase in temperature enables more thermal energy to be transboiling point of uranium, thus resulting in a gaseous core. This temperature by allowing the core temperature to increase beyond the gas-core NTP system attempts to overcome this issue of limited cation) place the solid-core I^{sp} in the range of 800-1100 seconds.

duct a detailed study of the SRGCR system of the Emerald City. Impor tant parameters were determined, it was then possible to conduct a detailed study of the SRGCR system of the Emerald City. If the SRGCR is ever developed, once the propulsion system and discussed in Reference 7, and were felt to be reasonably obtainable these values fell within the range of thrusts and I_{sp} 's that were

$$F_i = 4.4 \times 10^5 \text{ N.}$$

$$I_{sp} = 5000 \text{ seconds}$$

SRGCR in the remainder of this report are of thrust and I_{sp} that were used as representative figures for the chosen as the propulsion system for the Emerald City. The values thus, the open-cycle engine (hereafter referred to as SRGCR) was

Thrust (N)	m_e (kg)	I_{sp} (sec)
444,750	213,350	6000
177,900	101,440	5500
22,240	36,280	2400

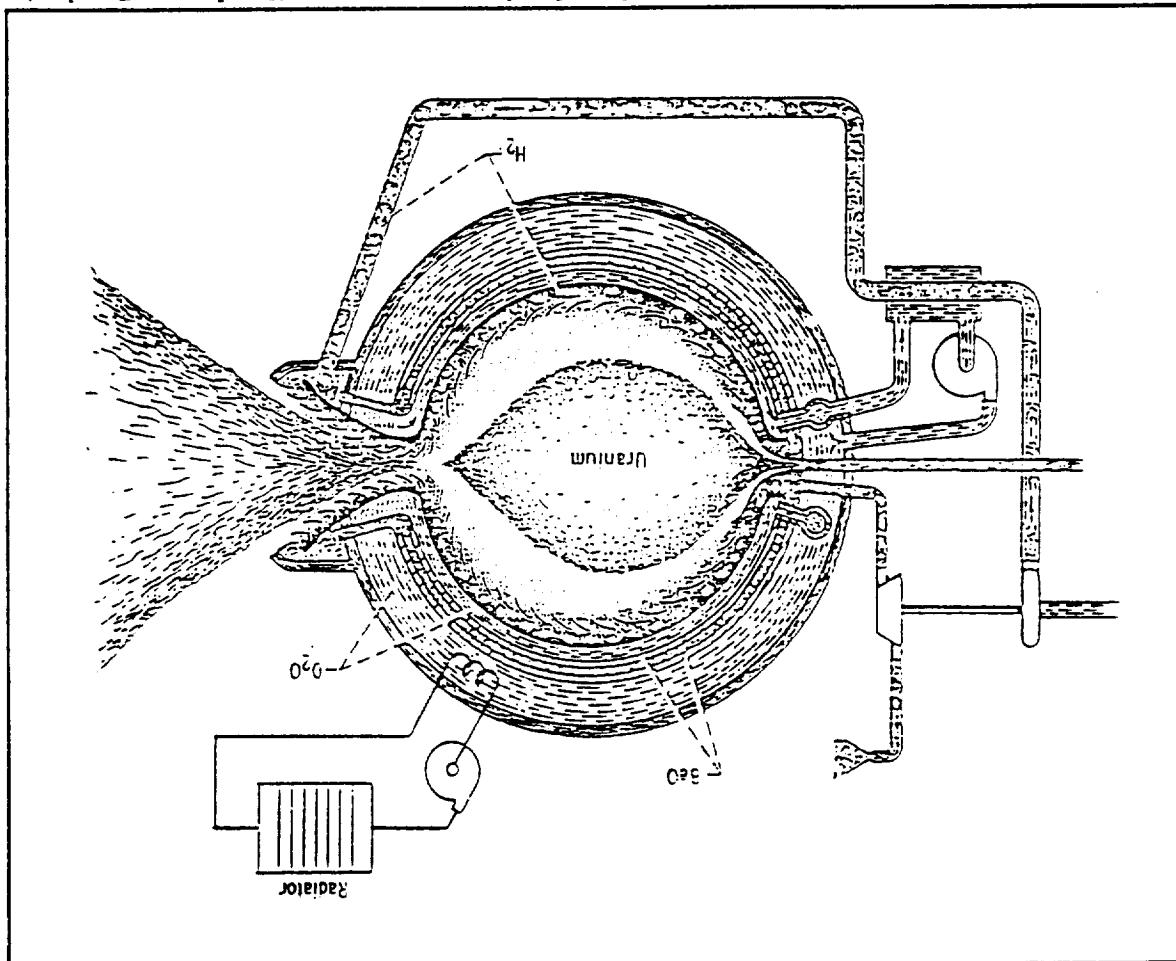
SRGCR DATA

Thrust (N)	m_e (kg)	I_{sp} (sec)
4,002,800	385,500	2635
1,334,200	34,475	2355
133,370	14,050	1780

LBCNR DATA

the closed-cycle engine has a significantly lower specific impulse value for the closed-cycle system is higher than that of the open than the open-cycle engine. However, the maximum expected thrust cycle engine. It will Table 3.1 - Comparison of I_{sp} , F, and m_e for LBCNR and SRGCR be shown later in this chapter in Figure 3.5 that the advantage of producing higher thrust decreases as the thrust level increases. It was felt that the closed-cycle engines had I_{sp} values that were too low for use by the Emerald City, and

FIGURE 3.3 - CONCEPTUAL SKETCH OF THE GAS-CORE NUCLEAR ROCKET



With the specific propulsive system determined and values for I_{sp} and F_1 known, it was then possible to perform a more detailed study of this system. Because the SRCNR is so conceptual in nature, there are many unanswered questions about its form and function. Figure 3.3 is a schematic of the GCNR that was conceptually developed at NASA Lewis Research Center by Mr. Robert Ragsdale. The main mechanical components of this engine are the pressure shell, the moderator, the turbopump, the nozzle, and the radiator.

3.2 SPACE RADIATED GAS-CORE NUCLEAR ROCKET STUDY

considered to be reasonable estimates of the operating conditions newtons, $D_c = 3.3$ meters, and $V_u/V_c = 0.23$. These figures were values were selected to be $I_{sp} = 5000$ seconds, $F_i = 4.4 \times 10^5$ volume of the cavity, V_u/V_c . For the data in Table 3.2, these and the ratio of the volume of the gaseous uranium core to the may be calculated. These inputs are I_{sp} , F_i , cavity diameter, D_c , four inputs that need to be determined before the other parameters this program may be found tabulated in Table 3.2. The program has for estimating the mass of an engine. The results obtained from SRGNR from general equations and equations given by Mr. Ragsdale this program was used to generate the important parameters of the written during this study, which can be found listed in Appendix B. written then possible to compute various important engine characteristics. These computations were done using a computer program Once a working knowledge of the engine had been acquired, it cannot be removed by the hydrogen alone.

used to remove any excess heat that builds up in the engine which encloses the core, cavity, and moderator, while the radiator is which aids in sustaining the fission process. The pressure shell used to reflect and reduce the energy of (thermalize) the neutrons is expelled through the nozzle to produce thrust. The moderator is process. The hydrogen absorbs heat from the fissioning uranium and cavity where the uranium isotope, 233 , is undergoing the fission aid in heat removal there. Then, the hydrogen is pumped into the liquid hydrogen is pumped through the moderator by the turbopump to radiator, which work together in the following manner. First,

Table 3.2 - Engine Parameters of a SRGCR, $E_i = 4.4 \times 10^5 \text{ N}$, $I_{sp} = 5000 \text{ s}$, Thrust = 440000.00 N, $V_u/V_g = .23$, $D_g = 3.30 \text{ m}$

SPECIFIED VALUES:**CALCULATED ENGINE PARAMETERS:**

$T(H_2) = 25165.49 \text{ K}$
 $\text{Cavity Pressure} = 981.25 \text{ atm}$
 $\text{Cavity Volume} = 18.82 \text{ m}^3$
 $\text{Uranium Volume} = 4.33 \text{ m}^3$
 $\text{Uranium Density} = 9.27 \text{ kg/m}^3$
 $\text{Gamma} = 1.261$
 $\text{Hydrogen Molecular Mass} = 0.759$

$H_2\text{-To-}H_2\text{ Rate} = 393.89$
 $H_2 = 8.951 \text{ kg/s}$
 Mass Flow Rates:
 $P_{propellant} = 8.97 \text{ kg/s}$
 $U_{23} = 0.023 \text{ kg/s}$

ENGINE DIMENSIONS:
 $\text{Pressure Sheel Thickness} = 0.087 \text{ m}$
 $\text{Radiator Mass} = 46632 \text{ kg}$
 $\text{Exhaust Nozzle Mass} = 233 \text{ kg}$
 $\text{Total Engine Mass} = 238682 \text{ kg}$
 $\text{Radiator Sheel Mass} = 52597 \text{ kg}$
 $\text{Turbo Pump Mass} = 773 \text{ kg}$
 $\text{Moderator Thickness} = 0.76 \text{ m}$
 $\text{Reactor Power} = 16185.08 \text{ MW}$
 $\text{Specific Heat} = 0.0224 \text{ kg/KW}$
 $\text{Thrust to Weight Ratio} = 0.188$

VARIOUS ENGINE PARAMETERS:
 $\text{Reacto Power} = 16185.08 \text{ MW}$
 $\text{Specific Heat} = 0.0224 \text{ kg/KW}$
 $\text{Thrust to Weight Ratio} = 0.188$
 $\text{Engine Efficiency} = 0.6665$
 $\text{Radiated Power} = 971.10 \text{ MW}$
 $\text{Jet Power} = 10787.32 \text{ MW}$

THROAT CONDITIONS:
 $\text{Temperature} = 22258.87 \text{ K}$
 $\text{Pressure} = 524.48 \text{ atm}$
 $\text{Gamma} = 1.246$
 $\text{Velocity} = 16542.23 \text{ m/s}$
 $\text{Area} = 0.843$
 $\text{Hydrogen Molecular Mass} = 2.004$

EXIT CONDITIONS:
 $\text{Temperature} = 4120.51 \text{ K}$
 $\text{Pressure} = 0.115 \text{ atm}$
 $\text{Gamma} = 1.226$
 $\text{Velocity} = 49033.25 \text{ m/s}$
 $\text{Area} = 0.6489 \text{ m}^2$
 $\text{Hydrogen Molecular Mass} = 2.004$
 $\text{Exit-To-Throat Area Ratio} = 300$
 $\text{Mach Number} = 6.50$

generated using an I_{sp} of 5000 seconds, an F_1 of 4.4×10^5 newtons, a range of different powered-flight times. This figure was setup between the number of engines required and the mission AV for Equation 3.3 is plotted in Figure 3.4, which shows the relation-

$$m_e = n m_a. \quad (3.4)$$

total engine mass from number of engines was determined, it was possible to calculate the number of engines was determined, once the was found by replacing j in Equation 3.2 with $NF_1 t_p$. Once the

$$n = \frac{m_a}{m_e I_{sp} g} \left(e^{\frac{F_1 t_p}{I_{sp}}} - 1 \right) \quad (3.3)$$

determined. This formula, given by engines, n , that would be required for any given mission had to be related to the propulsion system. For example, the total number of was then possible to proceed with other calculations that were once the SRGNR characteristics and values were obtained, it

all mass of the engine was found to be 238.7 metric tonnes. times what a standard chemical rocket can attain today. The over-exit velocity of 49 km/s. This value of exit velocity is over ten power of 16.1 gigawatts, a thrust-to-weight ratio of 0.19, and an temperature of 22,260 K, a jet power of 10.8 gigawatts, a reactor conditions are included with the program in Appendix B. Some of the more interesting results noted from Table 3.2 are a throat exit of the engine. The formulas that were used to calculate these calculate the conditions in the cavity, in the throat, and at the exit of the SRGNR engine. With these inputs, the program was able to

$$\frac{m}{m_0} = e^{-\frac{\Delta V}{I_{sp} g}} - \frac{I_{sp} g}{I_{sp} g + \frac{\Delta V}{g}} (1 - e^{-\frac{\Delta V}{I_{sp} g}}). \quad (3.5)$$

payload mass ratio, given by

was then possible to calculate the payload mass in the form of the may be determined. Once the total engine mass has been found, it number of engines for any selected mission parameters (ΔV , t_p , M_d) and an assumed dry mass of 1×10^6 kg. By using Equation 3.3, the

Figure 3.4 - Number of Engines vs. ΔV with Powered-Flight Time a Parameter

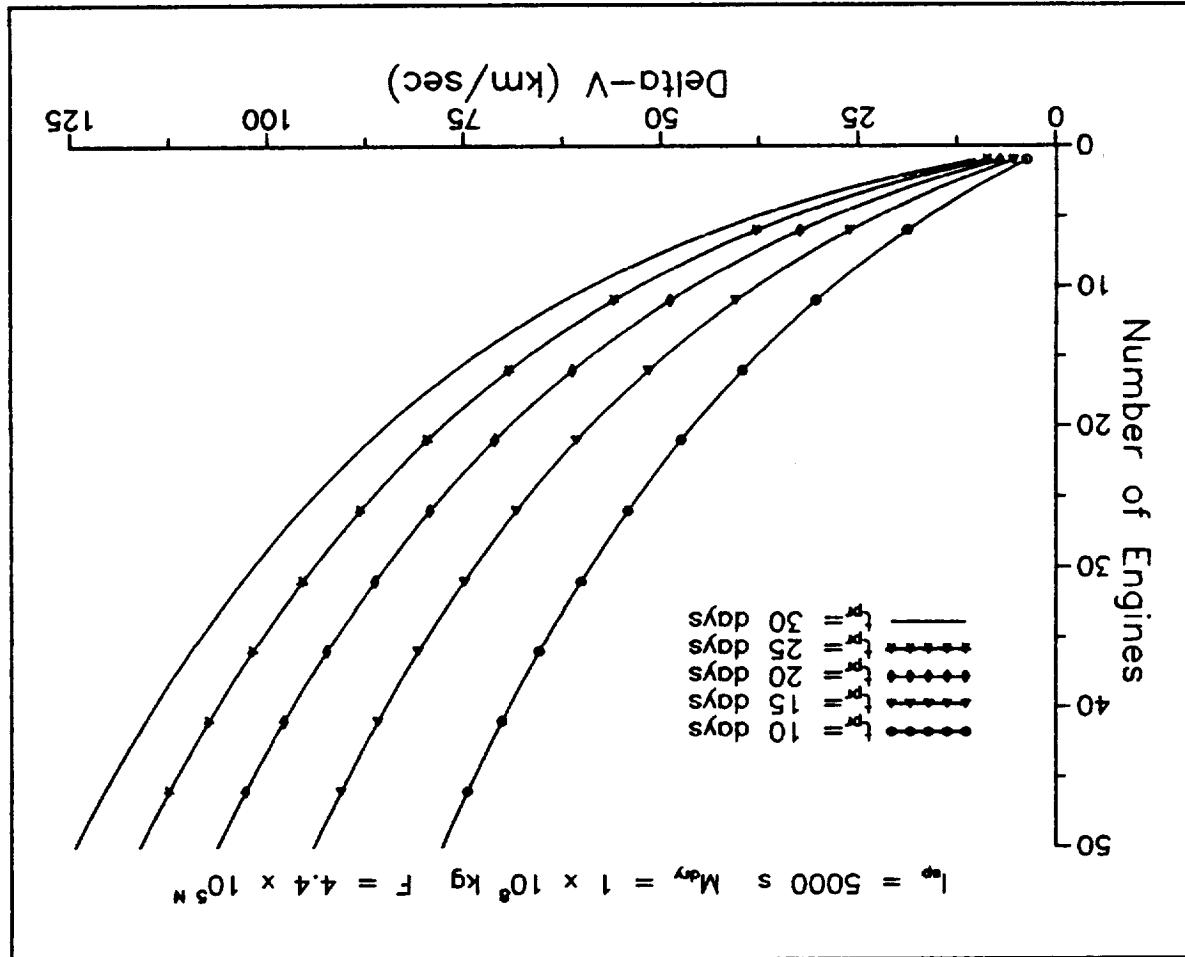
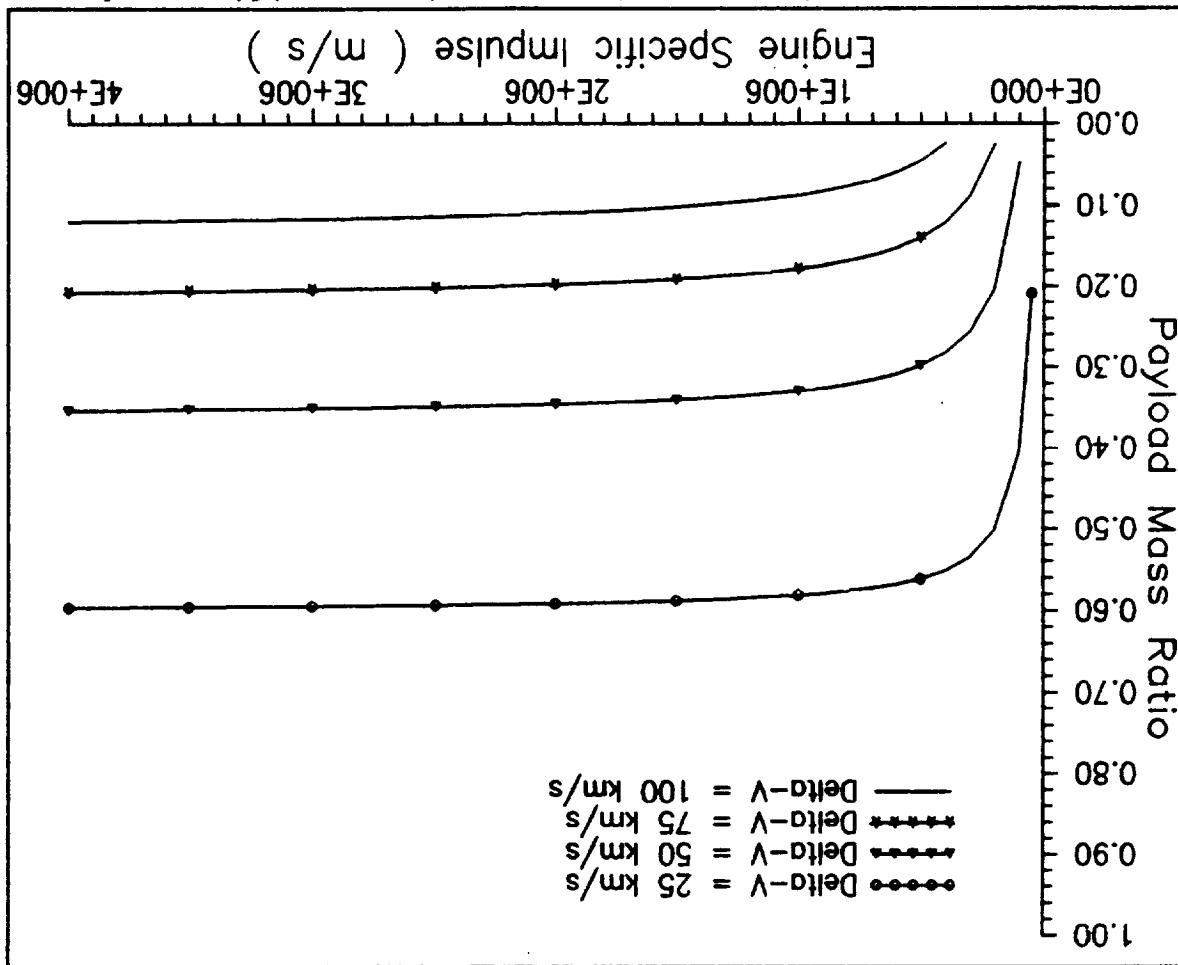


Figure 3.5 - Payload Mass Ratio vs. Engine Specific Impulse (I_{sp}) with ΔV as a Parameter.



Equation 3.5 was used to generate figure 3.5, which graphically shows the relationship between the payload mass ratio and the engine specific impulse I_{sp} for different mission ΔV's. An interesting note about this plot is that the payload mass ratio

is defined as the impulse produced per unit mass of the engine, or in equation 3.5, I_{sp} is defined as the engine specific impulse and

$$I_{sp} = \frac{F_i t}{m_i} \quad (3.6)$$

The preliminary propulsive system that was chosen was the space radiated open-cycle gas-core nuclear rocket engine. The benefits of this system are its high I_{sp} and thrust values that can be obtained. However, this engine is still very conceptual in nature, and so it is not currently known if the idea will eventually lead to a functioning rocket engine or not. It can be seen from Table 3.2 that the temperature in the throat of the

found in Chapter 6.

city, using the equations derived here. These masses can be for specific masses. Two masses were designed for the Emerald City. This is a crucial step in the design of the Emerald City. These masses can be found for different mass specie given here, these masses can be found for different mass and figures system and propellant required. By using the equations and figures to find equations that would yield the total mass of the propulsive system to end result of the analysis presented in this chapter was

3.3 CONCLUSIONS

The end result of the analysis presented in this chapter was pay load mass, and thus the pay load mass ratio will be negative. A value of I_{sp} below which, the engine mass exceeds the entire level off. Also, it may be noted from Equation 3.5 that there is I_{sp} has reached the point where the pay load mass ratio begins to or the powered-flight time or decreasing the engine mass once the increases. There is little to be gained by increasing the thrust operating in the region where the pay load mass ratio substantially is increased. Thus, an increase in the I_{sp} is only beneficial when tends to level out no matter how much the engine specific impulse

needed for Project WISH in the mid-21st century.

engrane capable of generating the high impulse-high I_{sp} combination cycle gas-core engine will remain as the only type of nuclear less massive ship, smaller AV's... until then, however, the open scope of Project WISH were to ever be reduced, i.e. fewer people, open cycle engine. The light bulb engine could prove useful if the this engine is not foreseen to have an I_{sp} as high as that of the gas-core engine, which is a closed-cycle type of engine. However, both of these problems can be lessened by going to a light-bulb which will result in massive shielding requirements for the crew. amounts of radioactive material are present in the exhaust plume concern of the radiation generated by this type of engine. Large the second side effect is the environmental and human factors uranium will be lost per engine per day of powered-flight time. nozzle. It was estimated that approximately 2 metric tonnes of effects was the loss of uranium out of the cavity and through the open-cycle engine, both of which are related. The first of these there were two detrimental side effects noted by using the fission.

concept of an open-cycle gas-core reactor is ever to reach gases. This area will need to be thoroughly researched if the is envisioned that the core will be confined by a vortex of inert development is the confinement of the gaseous core. Currently, it withstands this kind of thermal load. Another area in need of have to be made in the development of materials capable of nozzle is predicted to be around 22,000 kN. Clearly, advances will

considered in detail during the third year (1991-1992) of the year using a lumped-mass modelling method, and will again be dynamics was not considered in this analysis, it was examined last i.e. there are no deflections present. Although structural investigation, the Emerald City was considered to be a rigid body, loads encountered. However, for the purpose of this preliminary there will be some structural deflections that arise due to the For a body that is as large and complex as the Emerald City,

4.1 ATTITUDE DYNAMICS BACKGROUND

chapter.

perform these attitude control studies are the focus of this equilibrium following a disturbance. The methodologies used to control requirements needed to return the Emerald City to known, attitude control studies were conducted in order to find the Phase I study conducted last year. Once these configurations were configurations had to be determined, which was done during the will be gyroscopic in nature. Therefore, stable equilibrium spinning to produce artificial gravity (see Chapter 5), the system attitude due to disturbances. Because the Emerald City will be the fact that it will be necessary to damp out oscillations in attitude control is an important facet of Project WISH due to

4.0 INTRODUCTION

ATTITUDE CONTROL

CHAPTER 4

Once the stable configurations of the Emerald City are known, the control aspect of the problem may be examined. The main goal

4.2 CONTROL SYSTEM REQUIREMENTS

(determined by the nominal orbit).

Artificial gravity considerations), and orbital angular velocity (determined by ship configuration), spin rate (determined from depends upon three principal factors: mass moments of inertia (determined by ship configuration), spin rate of the Emerald City thus, it may be seen that the stability of the Emerald City axes (see schematic in Chapter 6), and α is the spin rate of the where I_z and I_x are the mass moments of inertia about the z - and x -

$$b = \alpha / g = \text{spin rate} / \text{orbital angular rate}$$

$$r = I_z / I_x = \text{slenderness ratio}$$

The parameters b and r are given by

$$3. b < 4/r - 3 \text{ and } r < 1.$$

$$2. b < 1/r \text{ and } r > 1$$

$$1. b > 1/r \text{ and } b > 4/r - 3$$

The parameters b and r in the following manner:

As stated earlier, the stable equilibrium configurations for the Emerald City were determined from last year's vehicle dynamics study. These stable configurations were found to be dependent on

the requirements, it was felt that the rigid body assumption was

obtained an order of magnitude estimation of the control thrusts per

project. Since the goal of the attitude control study was to

adequate.

(MATLAB® software) was used to obtain the non-dimensional state disturbances. A linear quadratic regulator control program given ship configurations, thrust input configurations, and initial is used to simulate the state response of the Emerald City for thrusters ("denotes non-dimensionalized quantities). Equation 4.1 and $\dot{[x]}$ is the non-dimensional torque provided by the control

$$[\dot{x}] = \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix}$$

$$[B] = \begin{bmatrix} 0 & 1 \\ 1 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

(4.2)

$$[A] = \begin{bmatrix} 0 & (1-x) & (x-2) & 0 \\ (1-x) & 0 & 0 & (2-x) \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

where

$$\ddot{x} = [A][\dot{x}] + [B][\dot{y}] \quad (4.1)$$

formulation

This equation was expressed in the non-dimensional state-space state-space equations that model the motion of the Emerald City. The first step in achieving this goal was to determine the

4.2.1 State Feedback Control Design

of the attitude control study was to determine the values of thrust, root-mean-square power, and propellant mass required to damp out an initial disturbance.

$$A_{T^*}^{G_1} + P^* A_G + G_0 T^{G-1} G = 0 \quad (4.7)$$

solution of the linear matrix equation
for any initial disturbance state x_0 . The power matrix P^* is the

$$S^* = X_0 P^* X_0 \quad (4.6)$$

which yields

$$S^* = \int_0^\infty T^{G-1} G dt \quad (4.5)$$

control power consumed can be found by the non-dimensional power
For the control torques of Equation 4.4, the non-dimensional

4.2.2 Attitude Control Power Required

Equation 4.3.

where G is the control feedback gain matrix minimizing the CDPI in

$$[T] = [G][X] \quad (4.4)$$

yields a linear state feedback control law
total control effort and the kinetic energy of the system and
By minimizing this performance index, the program minimizes the

$$CDPI = \frac{1}{2} \int_0^\infty (X^T X + T^T T) dt. \quad (4.3)$$

defined by
response that minimizes the control design performance index,

$$T = \rho I^2 n^2. \quad (4.13)$$

$$F_i = \rho I^2 \frac{D^2}{n^2}. \quad (4.12)$$

$$t_{con} = \frac{n}{\rho} \quad (4.11)$$

$$\begin{bmatrix} \theta_1 & \theta_2 & \dot{\theta}_1 & \dot{\theta}_2 \end{bmatrix} - \begin{bmatrix} \theta_1 & \theta_2 & \dot{\theta}_1 & \dot{\theta}_2 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & n \\ 0 & 0 & n & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \quad (4.10)$$

The various dimensional and non-dimensional quantities are related by previous equations.

The various dimensional and non-dimensional quantities are related by previous equations. The required quantities and matrices in the equations 4.4 through 4.9 can be evaluated by using any suitable control software such as the MATLAB Control Toolbox mentioned in equations 4.4 through 4.9 can be evaluated by using any suitable control software such as the MATLAB Control Toolbox mentioned in the previous section. The required quantities and matrices in the equations 4.4 through 4.9 can be evaluated by using any suitable control software such as the MATLAB Control Toolbox mentioned in the previous section.

$$\delta = D^{-1}[D] \quad (4.9)$$

and the non-dimensional thruster distribution matrix is defined by

$$A^{ij} = A + BG \quad (4.8)$$

where

control torques about the body axes. The number would depend on hundreds, perhaps thousands, of control thrusters to exert attitude for a body with the size of the Emerald City, one would need

4.2.4 Attitude Control Thruster Configuration

example Figure 6.4 for specific mission designs) dimensional thrust input versus non-dimensional time plots (see for Equation 4.16 is found by numerically integrating the non-where f is the total number of inputs used. The integral in

$$m_{p,coa} = \left(\frac{I_s A}{D_e V_{ex}} \right) \sum_{j=1}^{f-1} \int_{t_j}^{t_{j+1}} |f_j| dt \quad (4.16)$$

found by the formula
The propellant mass required for the control thrusters can be

4.2.3 Attitude Control Propellant Requirement

where V_{ex} is the exit velocity of the control thrusters.

$$P_{prop} = \frac{V_{ex} I_s A^2}{2 D_e} \sqrt{\frac{S_e}{t_c}} \quad (4.15)$$

power required is then given by the formula
computed via Equations 4.6 and 4.7. The root-mean-square control damp out a disturbance can then be found from the value of S_e , dimensional quantities. The root-mean-square power required to In all of the above equations, a "above a variable denotes non-

$$f_{coa} = D_e F \quad (4.14)$$

The non-dimensional control thrust forces can be obtained via

The methodology developed in this chapter can be used to study the attitude control of the Emerald City for a wide range of ship configurations, thrustuster configurations, and initial disturbances. Two particular scenarios were examined and the control system at this point and the control study can proceed.

4.3 ATTITUDE CONTROL DESIGN METHODOLOGY

Individual thrusters may exist at each cluster becomes immaterial for that particular input configuration. How many inputs, F_1 , F_2 , and F_3 , and the attitude control requirements are locations are shown as if there are only three control thruster subsequently. For example, in Figure 6.5, only three cluster outputs required in a particular cluster can be found of thrusters required to support the total number of given thrust capabilities of thrusters, the total number thus, for a particular location through the control study, one can then apporrtion equally the required thrust to individual thrusters. Particular location identified through the control study, the total thrust-time history at a control study. After finding the total thrust-time history at the location, each cluster location acts as one input in the production identical thrust-time histories in a given cluster obtained as the resultant force of hundreds of thrusters each cluster is represented as if it is a single thrust force one can instead consider only a few clusters of thrusters, where one can account so many thrusters individually in the attitude problem study would result in a very large D (thruster distribution) matrix. However, because the Emerald City is assumed rigid, taking the thrust output capabilities of the control thrusters. Taking

The outline of the methodology as described above is reviewed here. Results for particular mission studies can be found in Chapter 6. Requirements were determined using the methods provided above. The 4.9, to be studied and determine the slenderness ratio, r , 1. Choose a cluster configuration, characterized by Equation 4.9, to be studied and determine the slenderness ratio, r , 2. Use MATLAB (or a similar linear quadratic control disturbance to investigate. 3. Use MATLAB to find the control torque, T , and the state response, x , to Equation 4.1 that minimizes the regulator program) to determine the feedback gain, G , and control design performance measure of Equation 4.3. 4. Use MATLAB to find the control thrusts required, F , for the resulting cluster inputs, R (via Equation 4.14), versus time profiles, the non-dimensional power parameter, S , and observe the non-dimensional control time, t_g , from the and responsive plots.

4. The resultant cluster thrusts required, F , for the and propellant required can be found from Equations 4.15 and 4.16, respectively.

control system can be found from F and dimensionalizing according to Equation 4.12. The root-mean square power and a disturbance is proportional to the square of the spin rate, out a disturbance is proportional to the square of the spin rate, control study was that the root-mean-square power required to damp

One of the more important results obtained from the attitude

these mission designs can be found in Chapter 6.

system for the two missions of the Emerald City. The results of which is summarized above, was used to design the attitude control system for a wide variety of missions. This methodology, control studies for a wide variety of missions. This methodology requires. A methodology was established to perform attitude requirements. Project WISH focused on determining the attitude control system this year, the work on the dynamics and control aspect of

4.4 CONCLUSION

(see Chapter 5).

into account in human factors studies when the torus was designed power requirements for attitude control. This result was taken below 1 rpm (since for $n < 1$, $n < n$) in order to decrease the Equation 4.18 clearly shows the benefit of keeping the spin rate

$$P_{\text{ext}} = \left(\frac{2\pi}{60} \right)^2 \frac{n^2 g}{I_s} \sqrt{\frac{t_s}{S_s}}. \quad (4.18)$$

rate to rpm's yields

Inserting this equation into Equation 4.7 and converting the spin where the spin rate n_s is now in revolutions per minute (rpm's).

$$D_s = \frac{n_s g}{2\pi} \left(\frac{60}{2\pi} \right)^2 \quad (4.17)$$

(see Chapter 5) as

written in terms of the spin rate and the g-level to be provided as shown in Equation 4.15. However, the torus diameter, D_s , can be

5.1

recombined into products that cannot be recycled. More importantly necessary to prevent compounds such as air or water from being run (unrealistically) with one-hundred percent efficiency. This is times expected for Emerald City, all of these systems would have to using mechanical systems. Because of the three year plus mission management, and so forth. However, there are two major faults with for air revitalization, temperature and humidity control, waste approached using mechanical systems. Separate systems were used last year, the different functions of life support were

5.1 LIFE SUPPORT SYSTEM

gravity, and the problem of radiation.

spacecraft: the life support system, the need for artificial covers three topics that relate directly to the design of the factors will play an important role in its design. This chapter fifty years. Because of the magnitude of the Emerald City, human with a crew of between 500 and 1000 and an operational lifetime of becomes a problem that could dominate the design of a spacecraft supply, which is a relatively minor concern on a shuttle mission, long that environment is to be maintained. Something such as food with varying degrees of difficulty depending upon its size and how maintaining a habitable environment in space presents problems

5.0 INTRODUCTION

HUMAN FACTORS

CHAPTER 5

though, is that since these systems are mechanical, they are subject to breakdown and will eventually need spare parts. Storing these parts or making provisions for their manufacture would waste valuable space and add extra mass to the ship. For these reasons, another concept was explored for the primary life support system: a biosphere is a totally enclosed ecological system, with biomes creating internal energy as its only input. The collective biomass of the earth is referred to as Biosphere I. Since all air, water, and waste is recycled internally, life can be sustained indefinitely. Clairs Flasque, the flask contains only simple organisms, but it has been alive since it was sealed in 1968. What is proposed for Project Biosphere II is that a scaled and more efficient version of Biosphere I be used as the primary life support system. Research is already being done to create biospheres large enough for human occupation. The Biosphere II project in Oracle, Arizona has constructed an environmental facility sealed off from the atmosphere that uses its total recycling of all atmospheric carbon dioxide takes place in land and water four and ten times as efficiently as Biosphere I. Half a day instead of eight years. The 150,000 cubic meter facility is designed as an environment for eight people who were recently sealed inside for a two year study. This figures to roughly 19,000 cubic meters per person. Even though this number would probably shrink if research were devoted to reducing the volume needed per person, it was used for sizing the crew section.

5.1. Since the volume requirement (from Section 5.1) and shape for distance from the spinning axis, and g-level is shown in Figure 5.1, can be found. The relationship between rotation rate, able power and mass savings can be made if an acceptable lower g-limite can be found. Even though providing g would eliminate these effects, consider about a central hub to provide some level of artificial gravity. the crew section of Emerald City was designed as a torus rotating astronaut were injured or became ill. To counter these effects, harmless condition could pose a serious health problem if an to a drop in the production of red blood cells. This otherwise could be described as "space anemia" also occurs¹². This is due bones decalcify and muscles weaken and atrophy. A condition that zero-g on the body, none of it is very positive. Without gravity, of the little information known about long term effects of

5.2 ARTIFICIAL GRAVITY AND SHIP DESIGN

magnitude of Project WISH.

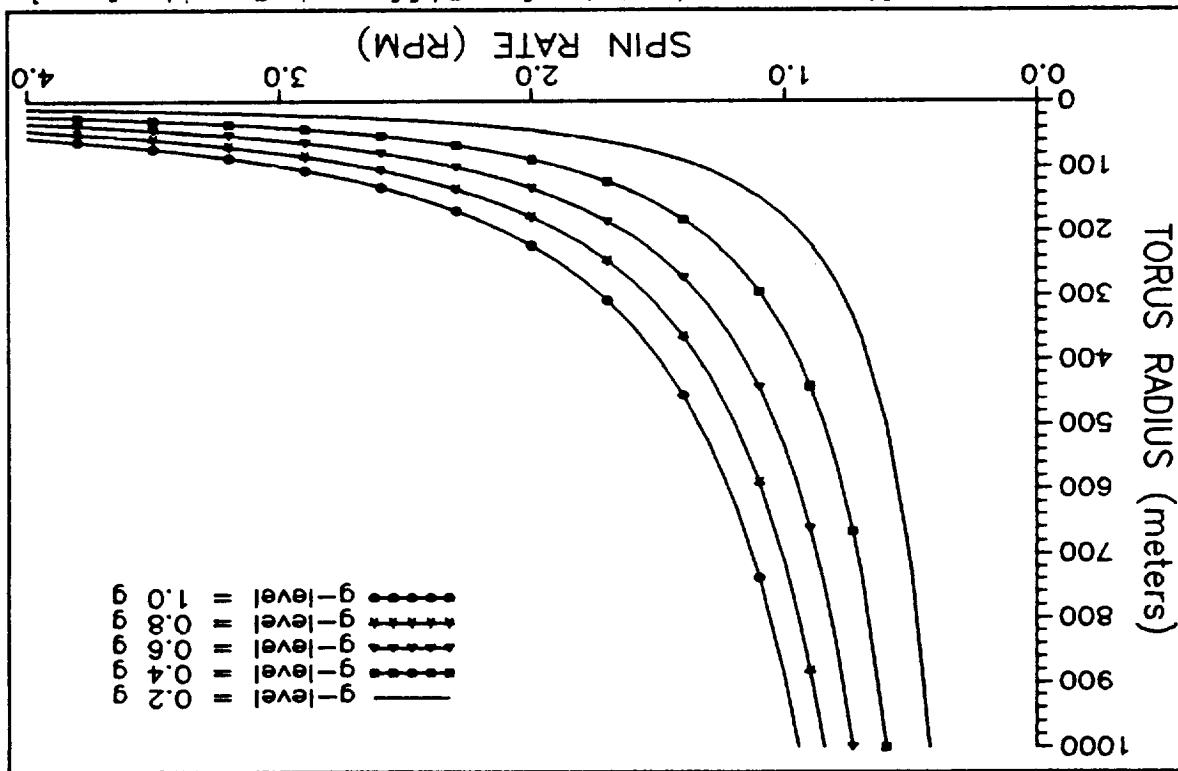
It was believed that the concept of biospheres could legitimate and to possibly extend man made biospheres onto other planets. Research is currently aimed at understanding more about Biosphere where N is the number of crew members on the Emerald City.

$$V_{\text{cyl}} = 19000N \quad (5.1)$$

Volume required in the torus section was then given by needs that have not yet been considered. The equation for the to allow extra space for manufacturing, food processing, or other

rpm was chosen as it was the most conservative limit found. To rpm². Although there is no universal agreement on this limit, it cannot endure extended periods of rotation at rates higher than 1 another reason behind this limit is human endurance. Most humans fourth power. This is discussed in greater detail in Chapter 4. the Emerald City is directly proportional to spin rate to the spin rate because the power needed to maintain the attitude of and spin rate. One revolution per minute is used as an upper limit (see Figure 6.1), is dependent on the constraints set for g-level listed in Table 5.1. Selection of the major radius of the torus, the g-level and spin rate desired. Several possible geometries are the crew section is known, the actual geometry is determined from

Figure 5.1 - Radius vs. Spin Rate for Different Gravity Levels



Another factor that contributes to the mass of the torus is the fact that it must hold an atmosphere. If a stressed skin is used, the necessary skin thickness and structural mass (M_s) of a torus, with major radius R and minor radius r , is found using the formulas shown on the top of the next page¹³. The first two formulas find the skin thicknesses needed to withstand the principal stresses on the surface of the torus. Generally, hoop is greater than meridional, so hoop is used to find the structural mass.

Structural mass is calculated for several configurations later in this chapter using the working stress (σ_y) and density (ρ) of

Gross of 1000							
Gross of 500							
Major radius (m)	Minor radius (m)	Change in δ	Outer radius (top-bot) (m)	Δ for σ_y (N/mm ²)	Δ for τ_{xy} (N/mm ²)	Δ for τ_{yy} (N/mm ²)	Δ for τ_{xz} (N/mm ²)
700	26.4	7.5	726	0.99	0.93	0.86	
660	27.2	8.2	687	1.02	0.95	0.88	
620	28.0	9.0	648	1.05	0.98	0.91	
580	29.0	10.0	609	1.08	1.01	0.94	
540	30.0	11.1	570	1.12	1.05	0.97	
500	31.2	12.5	531	1.16	1.09	1.01	
460	32.5	14.0	492	1.20	1.13	1.05	
420	34.0	15.6	453	1.24	1.16	1.08	
380	35.6	17.3	414	1.28	1.19	1.11	
340	37.3	19.1	375	1.32	1.21	1.13	
300	39.4	21.0	336	1.36	1.29	1.15	
260	41.6	23.0	297	1.40	1.32	1.20	
220	44.0	25.1	258	1.44	1.35	1.24	
180	46.5	27.3	219	1.48	1.37	1.27	
140	49.2	29.6	180	1.52	1.45	1.35	
100	52.0	32.0	141	1.56	1.48	1.38	
60	55.0	34.5	102	1.60	1.50	1.40	
20	58.0	37.1	63	1.64	1.48	1.32	

conservative mass, provides a g-level of only .8 g in the torus was considered. This lower gravity would hope-fully have only minor effects on the crew. Even though only .8 g in the torus was considered, the crew would have only a g-level of 1000. This lower gravity would hope-fully have only minor effects on the crew. Even though only .8 g in the torus was considered, the crew would have only a g-level of 500. This lower gravity would hope-fully have only minor effects on the crew. Even though only .8 g in the torus was considered, the crew would have only a g-level of 500. Furthermore, but more

Table 5.1 - Possible Torus Geometries

approximately 90 days over a 10 year period. What is needed for undertaken by the Emerald City, but for multiple missions of exploratory missions, such as a Mars mission or those that would be career assumed. This recommendation, however, is made not for Figure 5.2 is based on age at the start of exposure with a ten year exposure with a lifetime three percent excess risk of fatal cancer. Measurements¹¹, has recommended a career limit for whole body induced cancer. The National Council on Radiation Protection and the principle risk of living in space is from radiation

5.3 RADIATION AND SHIELDING

all calculations.

ship, a pressure of one atmosphere is used in the crew section for since structural mass is relatively minor compared to the whole would not carry as far, boiling temperature would be lowered, etc. coughing mechanism would be less effective, a normal speaking voice effects similar to living at higher altitudes on Earth: the atmospheric pressure (P_{atm}) inside. Doing this would also result in the torus. One way to reduce the structural mass is to lower the aluminum. P_g is the pressure due to the load distribution inside

$$M'' = 4\pi^2 R t_{loop} P$$

$$t_{loop} = \frac{g - pR}{2 \frac{R}{\pi} + \frac{\pi}{g} R} \quad (5.2)$$

$$t_{metabolic} = \frac{g}{P_{atm} X}$$

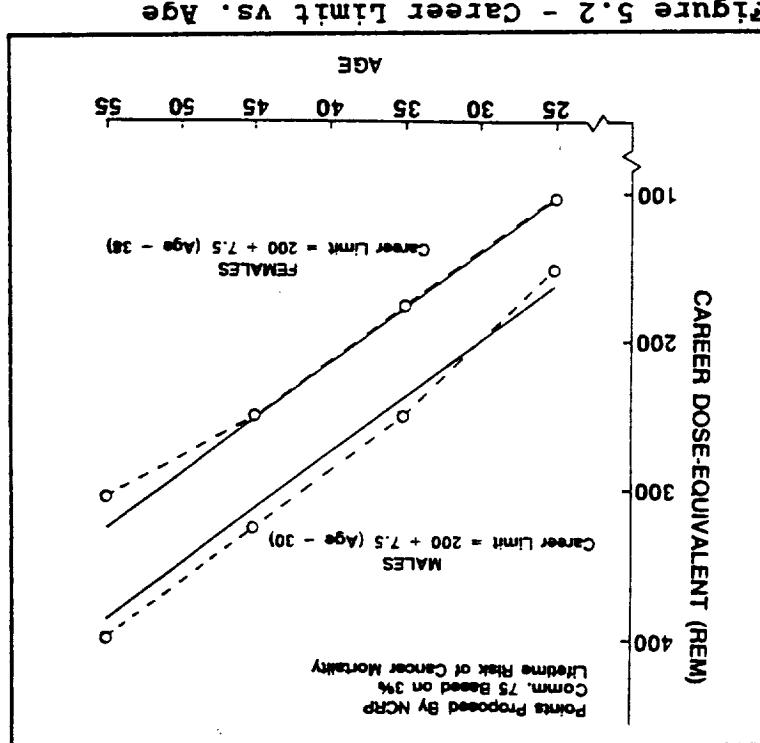
from 30 to 50 rem per
rays are estimated to be
dose rates from cosmic
activity. Unshielded
intensities, decreasing
relatively constant
radiation from solar flare
events, only during solar flare
activity. Unshielded
dose rates from cosmic
radiation at the source with a shield.
Cosmic rays are present throughout the
system, and the power system. Of these four, only the last two can
be reduced by moving the source away from the crew or by covering
the source with a shield. Cosmic rays are present throughout the
system, and the power system. Of these four, only the last two can
be reduced by moving the source away from the crew or by covering
the source with a shield.

Table 5.2 - Continuous Dose Limits
Major sources of radiation for Project WISH: galactic cosmic
 radiation, radiation from solar flare events, the population
 system, and the power system. Of these four, only the last two can
 be reduced by moving the source away from the crew or by covering
 the source with a shield. Cosmic rays are present throughout the
 system, and the power system. Of these four, only the last two can
 be reduced by moving the source away from the crew or by covering
 the source with a shield.

There are four

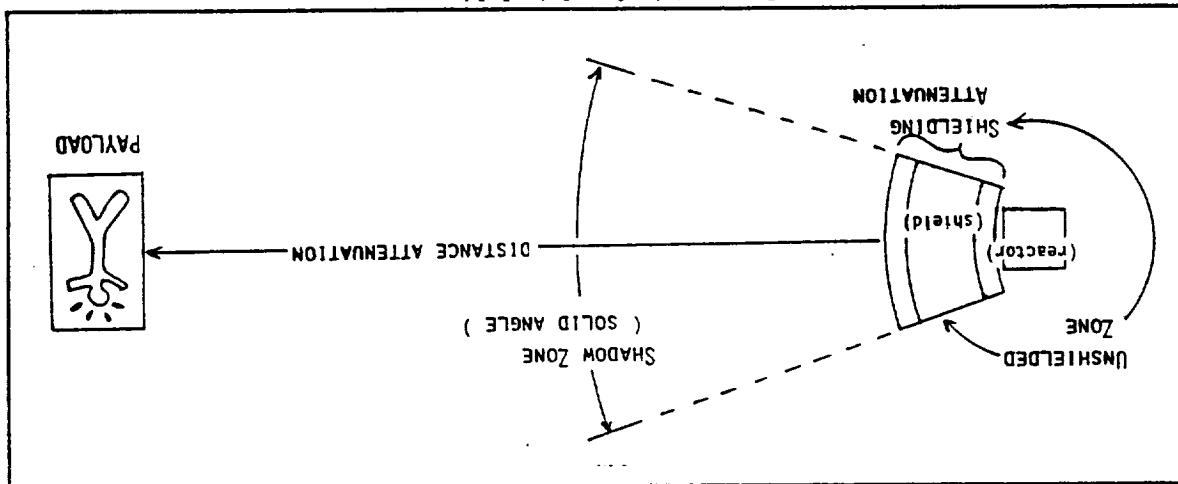
aid city.

Figure 5.2 - Career Limit vs. Age
Table 5.2 shows the
limits recommended for
constant public and
occupational exposure in
the United States. The
limit used on the Emer-
gency limit of 5 rem
exposure limit of 5 rem
per year would be the
occupational annual
annual limit used on the
Emergency limit.



and the engine, and the amount of time that fissile fragments primarily dependant on the amount of separation between the crew Chapter 3 using the formulas given by Charles Masser¹⁷. It is was calculated with the parameters of the gas-core engine from attenuation is to shield the crew section. The actual dose rate limits will only allow so much separation. The only other means of crew and the nozzle exit will reduce the dose rate, but structural back towards the crew section. Increasing the distance between the core rocket contains fissile fragments that emit gamma radiation

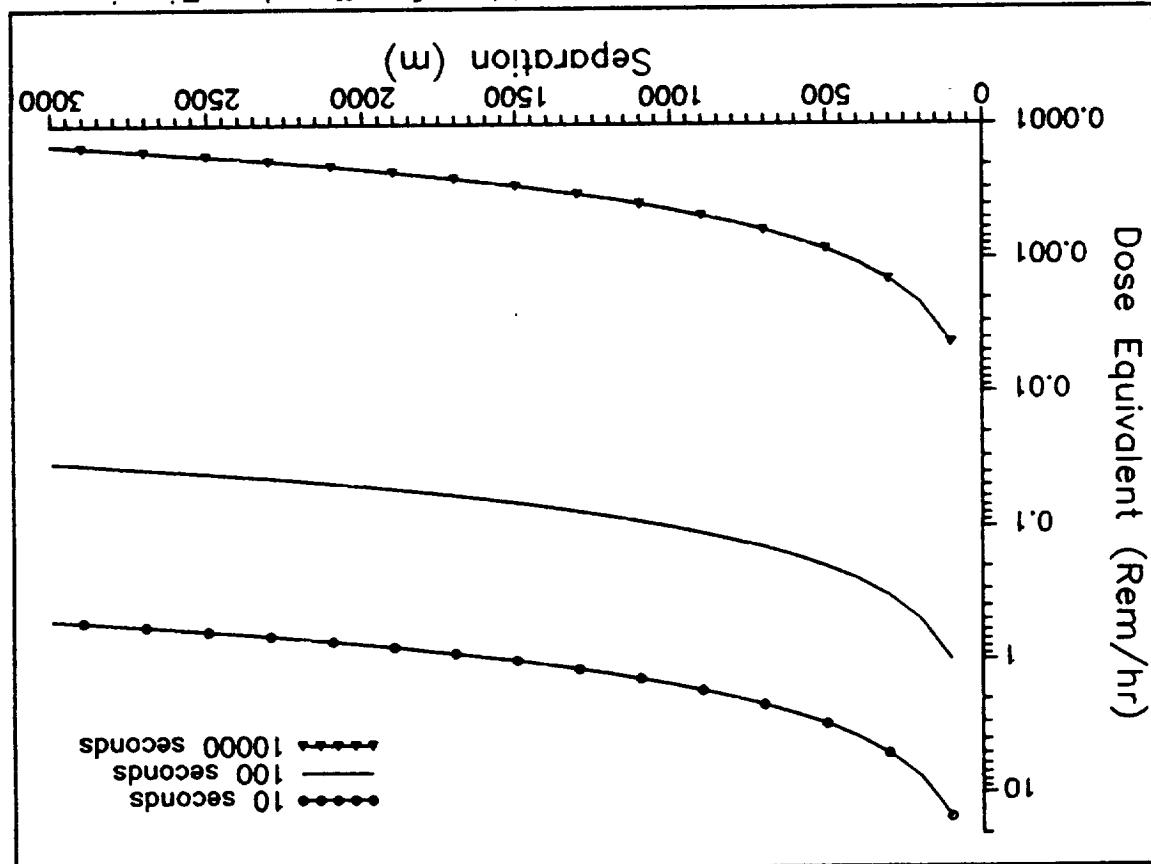
Figure 5.3 - Method of Partial Shielding



5.3). Unfortunately, the expanding plume of exhaust from the gas-separating them from the crew and by partial shielding (see Figure gaseous uranium core of the propulsion system can be attenuated by shielding the crew section. Radiation from the power system and the sources is impossible, the only way to protect them is to in excess of 1000 rem in only a week¹⁸. Since shielding these years, while large solar filters are capable of delivering doses

source of radiation because it is always present and cannot be galactic cosmic radiation is considered to be the primary the limited knowledge of radiation by the members of this project. is probably not accurate, it is one that had to be made because of the dose rate will be additive. Although this assumption engines, the dose rate will be additive. It has been assumed that for the case of multiple for one engine. Note that the numbers in Figure 5.4 are only about 100 seconds. Note that the numbers in Figure 5.4 are only of the gas-core engine comes from Masser, who estimates it to be about 100 seconds. The only estimate for the fission fragment retention time times. The only estimate for the fission fragment retention time this relationship for three different fission fragment retention remain in the core before exiting the nozzle. Figure 5.4 shows

Figure 5.4 - Dose Rate vs. Separation for Varying Fission



shed compares different materials and finds liquid hydrogen to be best attenuate radiation and still save mass were explored. Towns with only passive shielding remaining, materials that could affect.

neutrons, the more destructive types of radiation, are not shielded is that they only stop charged particles. Gamma rays and the smaller distances involved. Another common failing of the Allen belts around the Earth only much more dangerous considering inside the field. This would create something similar to the Van rejected because higher energy radiation could become trapped radiation fields inside the torus. An electromagnetic shield was vehicular activity and also generate lethal bremsstrahlung the surface of the torus¹⁸. This potential would limit extra- eliminated because a potential on the order of 3 GV is needed on radiations up to a certain energy level. Electrostatic fields were depending on how much power they receive, they only shield radiation. A drawback common to both field types is that, an electromagnetic or electrostatic field to repel incoming theoretical type of shielding is active shielding. It uses either a physical barrier between the source and the target. A more cosmic radiation. The most common method of shielding is passive primary form of shielding was based on protecting against galactic flares and engine exhaust will only be present for periods of about a week or two at a time. Because of this, the selection of a shiedded at the source. No matter what their intensity, solar

Even though all the considerations in this chapter have not been solved, enough has been determined to create a pattern that can be used to make an initial design for the Emerald City. The results of research in the areas of biospherics, microgravity, radiation, and other fields not yet considered will set the limits that help finalize any design. The information presented in this chapter will be used for a preliminary design of the Emerald City for two particular missions, which may be found in Chapter 6.

5.4 CONCLUSION

Very effective¹⁹. Liquid hydrogen is more effective than other materials because it contains no neutrons for the incident radiation to scatter upon collision. Table 5.3 shows that 100 grams per square centimeter will reduce the dose to below 5 rem per year. One hundred grams per square centimeter of liquid hydrogen corresponds to a shield thickness of 14 meters. The mass of this type of shield, as well as the structural mass, is found for four different torus configurations in Table 5.4. Notice that even if the crew size is cut in half, the masses for the torus do not significantly drop. This is because of the geometrical nature of a torus, a large volume change results in a relatively minor change in surface area.

crew size	major radius (m)	minor radius (m)	surface area (m ²)	shielded area (m ²)	structural mass (kg)	skin mass (kg)	thickness (cm)
500	700	26.4	7.296e+05	7.296e+08	3.027e+07	1.537	
500	520	30.6	6.282e+05	6.282e+08	2.407e+07	1.419	
1000	700	37.3	1.031e+06	1.031e+09	5.052e+07	1.815	
1000	500	44.2	8.725e+05	8.725e+08	4.101e+07	1.741	

Table 5.4 - Structural and Shielded Mass Estimates

thickness (g/cm ²)	dose equivalent, rem/TG, from	alpha's	protons	neutrons	skin dose equivalent (0 cm depth)	BPD dose equivalent (5 cm depth)	skin thickness (cm)
100.0	0.0	9.4	6.7	101.6	117.7		
3.0	0.2	6.6	2.7	31.8	41.3		
10.0	0.6	7.8	1.5	6.3	16.2		
25.0	0.8	8.1	0.4	0.4	9.7		
50.0	0.7	6.6	0.1	0.1	7.4		
75.0	0.6	4.8	<0.1	<0.1	5.4		
100.0	0.4	3.3	<0.1	<0.1	3.8		

Table 5.3 - Solar Minimum Galactic Cosmic Ray Depth Dose Equivalent in tissue as a function of particle type and LH₇ shield thickness

The procedure that was followed in the design of these missions is listed sequentially as follows.

6.1 PROCEDURE

Once the methodologies of the previous chapters have been formulated, two sample missions were examined in order to obtain some preliminary sizing and mass estimates for the Emerald City. A Saturn Envelope mission and the currently popular Earth-to-Mars mission were chosen as representative scenarios for this preliminary design. The design for these missions were determined by incorporating the orbital mechanics, propulsion, attitude control and human factors subsystems. Orbital mechanics (Chapter 2) was used to determine the number of engines and the total engine and propellant masses. These were then used to size the Emerald City in terms of masses. The propulsion system study (Chapter 3) was used to determine the number of engines and the total engine and propellant missions. The propulsion system study (Chapter 4) was used to determine the sizing of the torus, and the attitude control study (Chapter 5) was used to determine central pole, etc. Human factors (Chapter 6) was used to determine volume of propellant, engine spacing and location, length of masses. These were then used to size the Emerald City in terms of masses. The work laid down in the previous chapters in mind, it is now possible to proceed with the design of both missions.

6.0 INTRODUCTION

REPRESENTATIVE MISSION DESIGN

1. Obtain the ΔV required for each mission from orbital mechanics.
2. Set values for the specific impulse, I_{sp} , and the thrust per engine, F_i , for the propulsion system. The mass of each engine, m_i , is then found from the computer program of Appendix B.
3. Determine the torus mass, m_{torus} , from the masses of the biosphere, the shield, and the torus structure. These masses are dependent upon the number of crew members selected. The dry mass, m_{dry} , is then estimated by making allowances for the engine, cargo, and remaining subsystems as well as other systems that have yet to be sized (heat rejection, power, tankage, etc.).
4. Calculate the number of engines required and the total masses.
5. Calculate the payload mass, m_l , for the missions. This engine mass, m_e , for each mission.
6. Calculate the total initial mass, m_0 , and the propellant mass, m_p . The propellant mass ratio, m_p / m_0 , and the payload mass ratio, m_l / m_0 , are then found.
7. Calculate the volume of propellant required for the mission, V_p . Then, by estimating a stem radius, r_s , the height of propellant, h_p , can be found.

The results for the Saturn mission can be found in Tables 6.1. Some important values to note are the total initial mass, 4.16×10^9 kilograms, the number of engines, 172, the torus radius, 700 meters, and the height of the pole section, 1270 meters. The payload mass ratio for this mission was found to be 0.083, or 8.3% of the total initial mass is payload. It must be remembered,

longest powered-flight time would be the first one. The Emerald City is smaller for each of the burns, and hence the powered-flight times would not be the same. This is because the mass of the AV required would be the same. If the total power is found based on these total values and a given total powered-flight time of 20 days, but it should be kept in mind that the only the total AV and powered-flight time. The number of engines times required for the four separate burns were not considered, but for this mission, the individual AV's and the Powered-flight

the Martian colony and arrival time at Saturn. Interplanetary transfer ship require a particular launch date from Titan, and that the planetary alignments and limitations on the required to support the first manned exploration of Saturn's moon motivation for such a mission might be that the Emerald City is and that a three year flight time was essential. A possible the Emerald City was in a poor orientation (AV-wise) with Saturn than 50 km/s round trip, but for this mission, it was assumed that the transfers to Saturn can be made with AV's considerably less five years with this AV ceiling. It should be noted that many of Neptune and Pluto cannot be reached at all in flight times of up to

569 meters.

1.295×10^9 kg, the torus radius, 700 meters, and the pole height, important design values for this mission are the initial mass, and a 6.53 day terminal powered-flight time. Some of the other were found to be 33 engines, a 5 day initial powered-flight time, found. From Table 6.1, it can be seen that the results of this number of engines constant, the second powered-flight time was the number of engines required was determined. Then, keeping this 1.52 years. The first powered-flight time was set at 5 days and for a total AV of 12.6 km/s, and the flight time was found to be MULIMP program. The AV's were found to be 5.1 km/s and 7.5 km/s was determined by minimizing the AV for this launch date using the was scheduled to leave Earth on November 7, 2050 and the flight time down into the departure and arrival AV's. The mission was Martian colonies. For this mission, the AV required was broken just outside the Earth's sphere of influence, to the ever expanding colonists and supplies that had been shuttled to the Emerald City, Emerald City might be required to undertake, perhaps carrying new to Mars. This mission represents a more common mission than the The second mission that was examined was a transfer from 1 AU

6.2.2 Earth-to-Mars Mission

mass, etc.).

however, that the payload mass as defined here is the mass of the cargo plus the mass for any other systems that were not considered during Phase II (power systems, thermal rejection systems, tankage

People	Saturn Mission	Earth to Mars
ΔV_{total} (km/s)	50	12.6
ΔV_1 (km/s)	-	5.1
ΔV_2 (km/s)	-	7.5
F (Newtons)	4.4×10^5	4.4×10^5
I_{sp} (seconds)	5000	5000
t_{refuel} (days)	20	11.53
$t_{\text{refuel total}}$ (days)	-	5
t_{refuel} (days)	-	6.53
t_{refuel} (days)	-	172
number of engines	1.5 $\times 10^9$	1×10^9
m_{dry} (kg)	1.5×10^9	1×10^9
m_{fuels} (kg)	1.111×10^9	7.746×10^8
m_y (kg)	4.4376×10^7	8.514×10^6
m_z (kg)	3.457×10^8	2.165×10^8
m_x (kg)	2.658×10^9	2.947×10^8
m_a (kg)	4.16×10^9	1.295×10^9
m_p / m_a	0.639	0.228
m_p / m_a	0.083	0.167
V_{L2} (m ³)	3.742×10^7	4.151×10^6
x_{gate} (m)	100	50
h_p (m)	1200	528
h (m)	1270	569
R (m)	700	700
r_m (m)	37	26
I_z (kg m ²)	5.6144×10^{14}	3.8061×10^{14}
I_x, I_y (kg m ²)	9.9568×10^{14}	2.1731×10^{14}
τ (I_z / I_x)	0.563876	1.75154
max/min g-levels	0.8/0.72	0.8/0.74
n (spin rate, rpm)	0.99	0.99

Table 6.1 - Summary of Design Variables for Sample Missions

An attitude control system was designed for the two particular missions examined for a sample initial disturbance and a sample thrust configuration. Using the methodology developed in Chapter 4, the root-mean-square power, propellant mass, maximum thrust, and control time was determined, as may be seen in Table 6.2. Also, the state response, control torque profile, and thrust profile for

6.2.3 Attitude Control System Requirements

Figure 6.1 - Schematic of the Emerald City

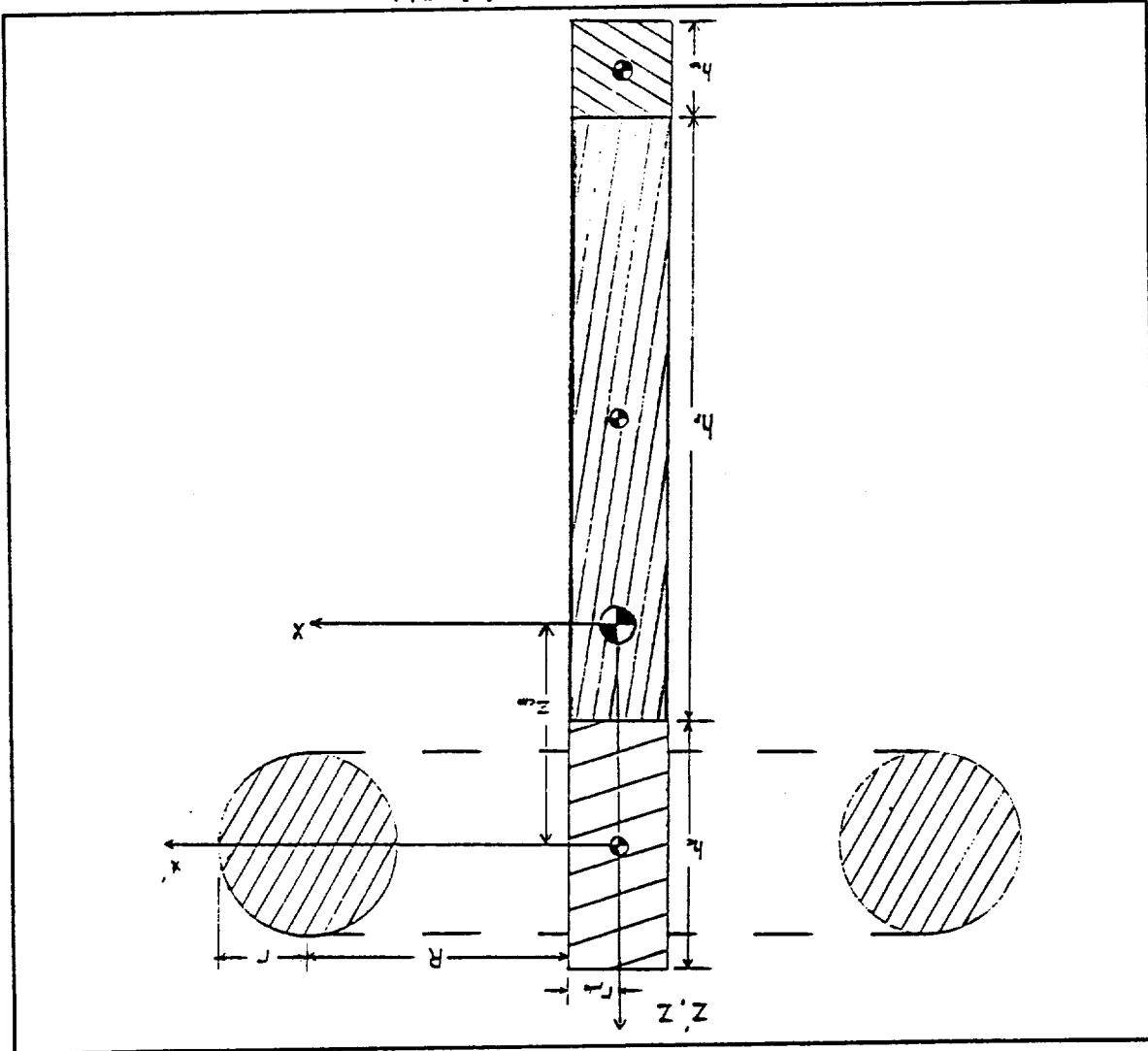
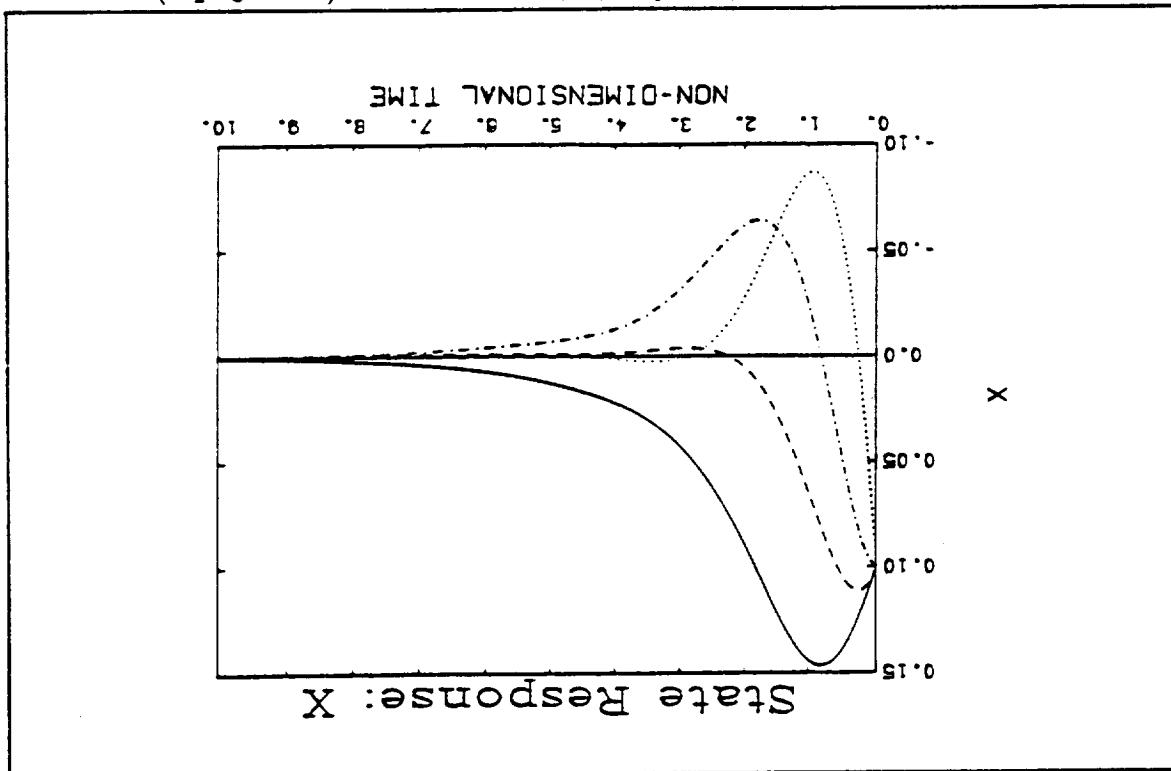
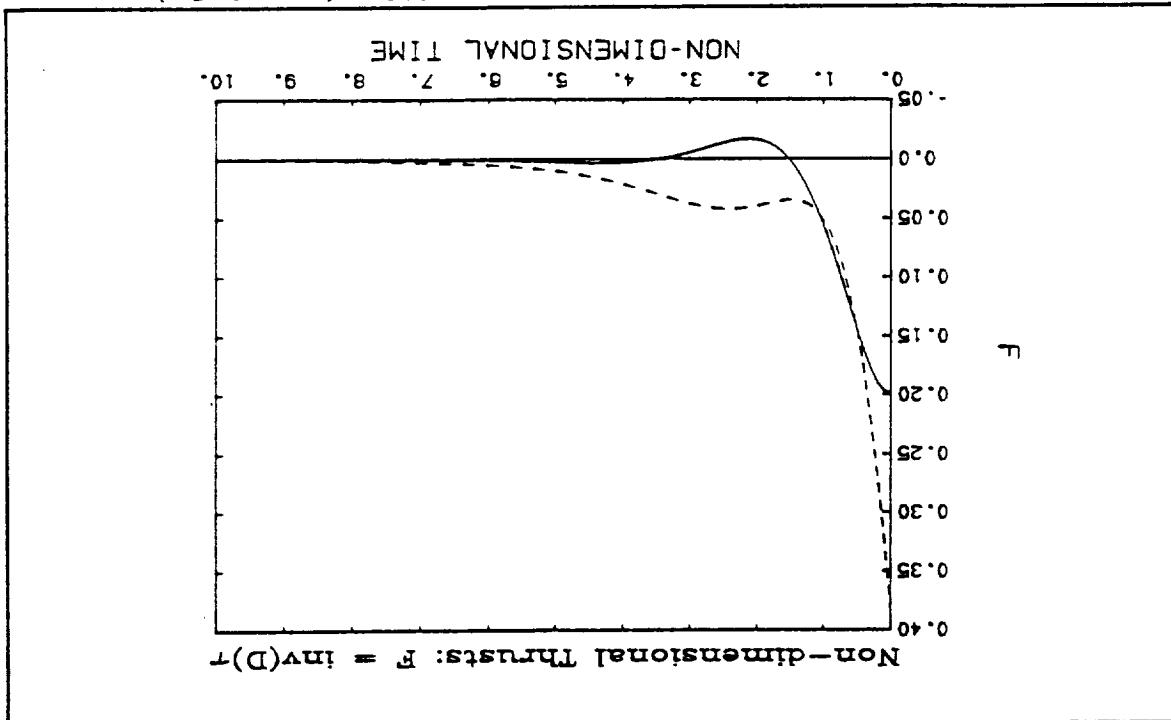
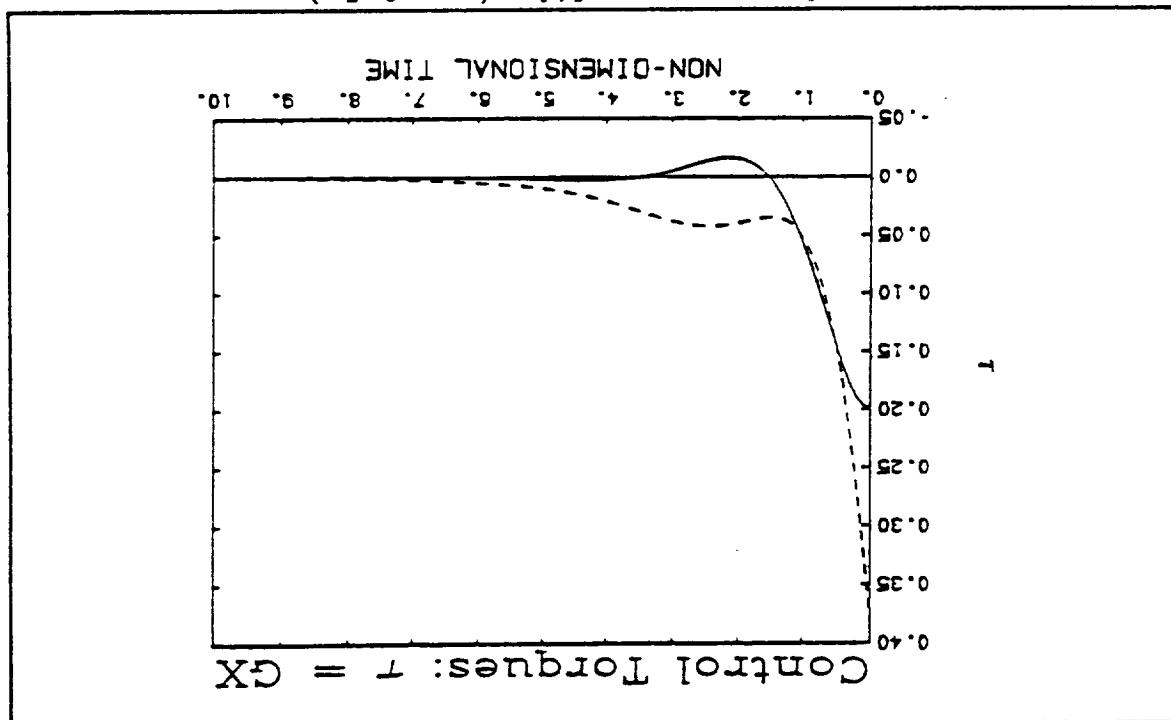


Figure 6.2 - Non-Dimensional State Response ($r = 0.5$)

I_1 / I_x	0.56	1.75	Initial Attitude
P_{rms} (Watts)	6.176×10^{12}	7.86×10^{11}	Power (rms)
$m_{payload}$ (kg)	2.105×10^7	3.458×10^6	Mass payload
$F_{cavitarl, max}$ (N)	2.988×10^9	1.911×10^9	Cavitarl force
$t_{control}$ (s)	- 100	- 100	Control time

Table 6.2 - Attitude Control System Requirements

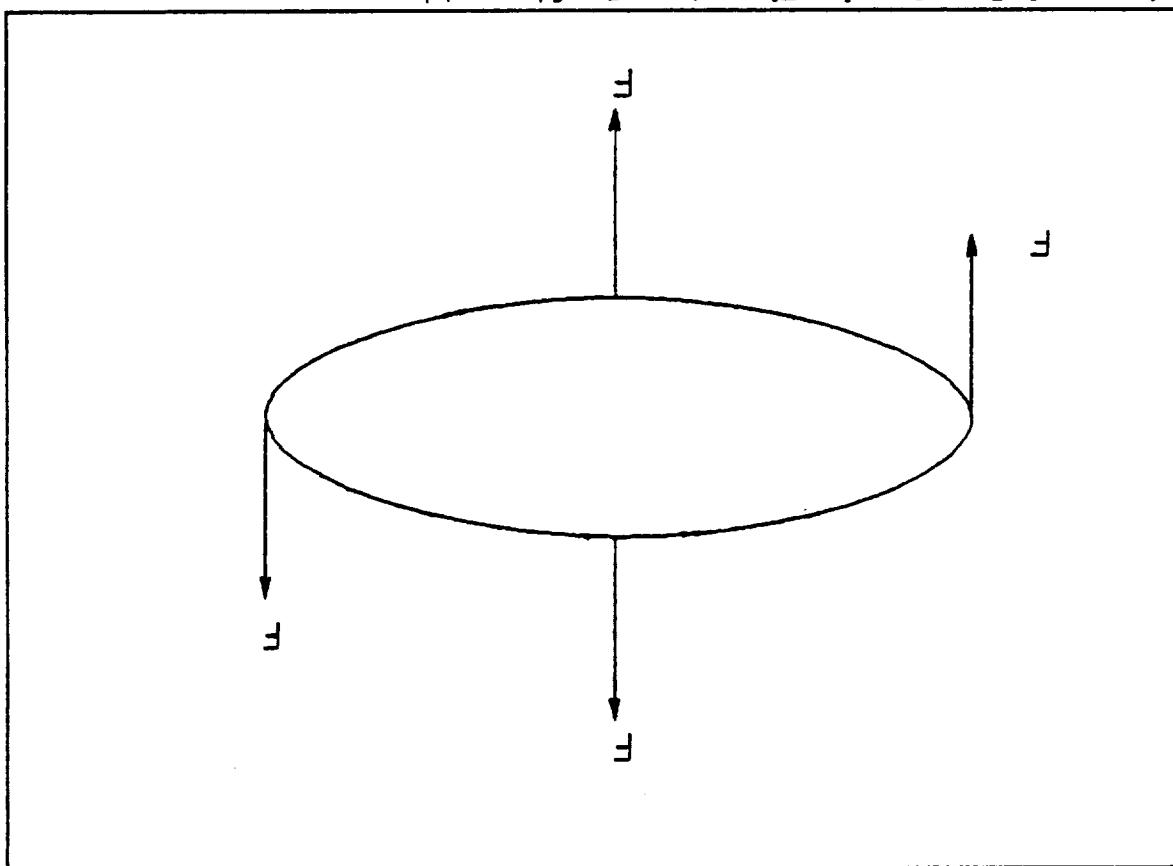
the Saturn Envelope mission configuration are shown in Figures 6.2-6.4 for the sample thruster configuration shown in Figure 6.5.

FIGURE 6.4 - Non-dimensional Thrust Profile ($r = 0.5$)FIGURE 6.3 - Control Torque Profile ($r = 0.5$)

accomplishment of the Phase II design of Project WISH. It is felt that this methodology is the main be examined. In the future, different initial disturbances, attitude thruster configurations, etc...., may mission parameters, such as crew size, AV requirements, sample the Emerald City may be determined. In the wide variety of missions may be looked at and the configuration for Emerald City. However, using the methodology established here, a wide variety of particular missions were examined for the Emerald City. In this chapter, two particular missions were examined for the

6.3 CONCLUSION

Figure 6.5 - Sample Thruster Configuration



such as the Emerald City.

examining these figures, one can realize the magnitude of a ship the estimated size and mass requirements of the Emerald City. By information from all of the subsystems studied, and provide data on the generation of Tables 6.1 and 6.2. These tables incorporated the cosmic radiation. The ultimate result of the Phase II study was encountered, and mass estimates were obtained for shielding from radiation shielding proved to be one of the major design problems the different levels of gravity that the crew would need. sustain life, while the torus size requirements were determined for shielding. Biospheres were examined as the primary method to problems of life support, artificial gravity, and radiation experienced by the Emerald City. Human factors looked at the thrust requirements needed to damp out a disturbance for attitude control, a methodology was established to determine the unit, and a detailed study was conducted on this type of engine. nuclear thermal propulsion system was chosen as the main propulsion for the Emerald City was determined. An open-cycle gas-core nominal orbit of 4 AU's was selected, and the operational envelope towards the design of the Emerald City. In orbital mechanics, a great deal

7.0 PROJECT SUMMARY

CONCLUSION

CHAPTER 7

<hr/> Table 7.1 - Envisaged Time Line for Project MISH <hr/>	
1989 - President Bush announces Mars Initiative to reach the Red Planet in 30 years.	
1991 - NASA presents a program to send sensing probes throughout the solar system. Projects include the return to the inner solar system, exploration of the asteroid belt, and further missions to the outer planets.	
1998 - Space Station Freedom becomes operational.	
2001 - Heavy Lift Launch Vehicle makes its maiden flight.	
2004 - Construction begins on a near-geosynchronous Earth orbiting space station.	
2009 - U.S. returns to the moon.	
2011 - Construction begins on the Moon Base.	- Maiden flight of National Aerospace Plane.
2015 - Moon Base becomes fully operational.	
2019 - First manned mission to Mars.	
2023 - First living modules constructed on Mars.	- Construction begins on reusable Interplanetary Ships (R.I.S.'s) for carrying personnel and cargo.
2028 - Mars Base becomes fully operational.	
2040 - Implementation of Project MISH.	
2050 - The Emerald City becomes operational.	

concessions to the unknown, we had best frankly recognize that irrational faith in the value of a new capability often plays an essential part in the early evolution of a new concept. Certainly, at that point, the lack of a recognized application is a demonstrably unsound basis for the concept's rejection."

$$(A.2)$$

$$V_r = \sqrt{\frac{R}{x_r}}$$

$$(A.1)$$

$$V_0 = \sqrt{\frac{R}{x_0}}$$

orbital velocity,

been assumed, V_0 and V_r are given by the formulas for circular since a circular nominal orbit and target planet orbit has values and the design variables of the problem.

Thus, the problem is to determine the relationships between these

$$5. a_0, t_{pr1}, t_{pr2}, t_{ff} > 0.$$

$$4. x_{ff,0} = x_{ff,T0}.$$

$$3. t_{pr1} + t_{pr2} < t_{pr,max}$$

$$2. a_0 < a_{0,max}$$

$$1. t_{ff} + t_{pr1} + t_{pr2} < t_{pr,max}$$

phase. The constraints were given in Chapter 2 as direction, which will be kept constant during each powered-flight where ΔV_1 and ΔV_2 are the velocity changes along the thrust vector

$$\Delta V_r - \Delta V_1 + \Delta V_2 - V_1 - V_0 + V_r - V_2 \quad (2.4)$$

set up in Chapter 2 was given by Equation 2.4

The objective function given for the ΔV minimization problem

EQUATIONS FOR ΔV MINIMIZATION PROBLEM

APPENDIX A

change is given by
for the second powered-light portion of the transfer, the velocity
for the first powered-light portion of the transfer. Similarly,

$$\Delta V_1 = V_{1P} - V_{0P} = - I_{sp}g \ln(1 - \frac{a_0 t_{P1}}{I_{sp}g}) \quad (A.6)$$

which becomes

$$V = V_1 - I_{sp}g \ln(1 - \frac{a_0 t_{P1}}{I_{sp}g}), \quad (A.5)$$

Integration yields
Inserting Equation A.4 into Equation A.3 and performing the
acceleration will increase with time according to Equation A.4.
with a constant thrust, it is expending mass, and thus the
This term arises from the fact that as the Emerald City is burning

$$a(t) = \frac{I_{sp}g}{a_0 t}. \quad (A.4)$$

term in this direction given by
was integrated along the direction of thrust, with an acceleration
(A.3)

equations for these velocities, the kinematic relationship
of the second powered-light phase, is more involved. To find the
first powered-light phase, and V_1 , the velocity at the beginning
however, finding the velocities V_1 , the velocity at the end of the
which are known for a given nominal orbit and target planet.

$$\Phi_{1,2} = \left(1 - \frac{a_{0,02} t_{px1,2}}{I_{sp} g}\right) \left[\ln\left(1 - \frac{a_{0,02} t_{px1,2}}{I_{sp} g}\right) - 1\right] + 1.$$

where
(A.10)

$$x_{1,f} = x_{0,2} + V_{0,2} t_{px1,2} + \frac{a_{0,02}}{\Phi_{1,2}} \frac{(I_{sp} g)^2}{(I_{sp} g)^2}$$

and the result was found to be
was integrated with the results from Equation A.5 inserted for V ,

$$dx = v dt \quad (A.9)$$

as was used to find Equation A.5, the relationships
equations and relationships. First, continuing in the same manner
The application of the constraint functions needed many more
where a_0^2 is not an independent variable, but given in Equation A.7.

$$\Delta V_x = -I_{sp} g \left[\ln\left(1 - \frac{a_{0,2} t_{px2}}{I_{sp} g}\right) + \ln\left(1 - \frac{a_{0,2} t_{px2}}{I_{sp} g}\right) \right]. \quad (A.8)$$

2.4 can be written as
by using Equations A.6 and A.7, the objective function of Equation
changed during a powered-light phase). It can easily be seen that
direction (it is assumed that the thrust angles, β_1, β_2 , will not be
the respective velocity vectors projected along the thrust
The subscript F in Equations A.6 and A.7 denotes the components of

$$a_{0,2} = \frac{I_{sp} g}{a_0 t_{px2}}.$$

where
(A.7)

$$\Delta V_x = V_{rF} - V_{2F} = -I_{sp} g \ln\left(1 - \frac{a_{0,2} t_{px2}}{I_{sp} g}\right)$$

known, the transfer orbit is defined by the following equations: the initial point of the free-fight trajectory (point 1) are θ_0 , t_{p1} , a_0 , and B_1 . Once the velocity and position vectors at where the known variables are r_0 and I_{sp}^s and the design variables

$$x_1 = \sqrt{x_{1x}^2 + x_{1y}^2}$$

$$\Phi = (1 - \frac{a_0 t_{p1}}{I_{sp} g}) [\ln(1 - \frac{I_{sp} g}{a_0 t_{p1}}) - 1] + 1$$

(A.12)

$$x_{1y} = x_0 \sin \theta_0 + \sqrt{\frac{x_0}{I_{sp} g} t_{p1} \cos \theta_0 + (\frac{I_{sp} g}{a_0})^2 \cos(B_1 - \theta_0) \Phi}$$

$$x_{1x} = x_0 \cos \theta_0 - \sqrt{\frac{x_0}{I_{sp} g} t_{p1} \sin \theta_0 + (\frac{I_{sp} g}{a_0})^2 \sin(B_1 - \theta_0) \Phi}$$

and

$$v_1 = \sqrt{v_{1x}^2 + v_{1y}^2}$$

$$v_{1y} = \sqrt{\frac{x_0}{I_{sp} g} \cos \theta_0 - I_{sp} g \cos(B_1 - \theta_0) \ln(1 - \frac{a_0 t_{p1}}{I_{sp} g})}$$

$$v_{1x} = -\sqrt{\frac{x_0}{I_{sp} g} \sin \theta_0 - I_{sp} g \sin(B_1 - \theta_0) \ln(1 - \frac{a_0 t_{p1}}{I_{sp} g})}$$

equations are given by

Equation A.10 yields the position along the direction of the thrust vector and the subscript 1, it means at position 1 or r_1 , etc. Thus, armed with Equations A.5, A.10, and some fundamental relationships from astrodynamics, the constraints can be related to the design variables of the problem in the following manner. First, the inertial X- and Y-components of the velocity and radius vectors at the end of the first powered-fight phase can be found by applying coordinate rotation matrices to Equations A.5 and A.10. These equations are given by

time of the transfer according to
 is the true anomaly at point 2. This then defines the free-fight
 calculated. The design variable that was designated was γ_7 , which
 the variables at the terminal free-fight point (point 2) may be
 orbit. Once the transfer orbit is defined through these equations,
 powered-fight time, and h is the angular momentum of the transfer
 the transfer orbit, τ_1 is the true anomaly at the end of the first
 specific energy of the transfer orbit, a is the semi-major axis of
 orbit, t_0 is the direction of the eccentricity vector, E is the
 In the above equations, e is the eccentricity of the transfer

$$h = \sqrt{a(1 - e^2)} \quad (A.18)$$

$$y_1 = \cos^{-1} \left(\frac{e_x}{x_1} \right) \quad (\text{quadrant}) \quad (A.17)$$

$$a = -\frac{2E}{h} \quad (A.16)$$

$$E = \frac{v_1^2}{2} - \frac{h}{r_1} \quad (A.15)$$

$$y_0 = \cos^{-1} \left(\frac{e_x}{x_0} \right) \quad (\text{quadrant}) \quad (A.14)$$

$$e_x = \sqrt{e_x^2 + e_y^2}$$

$$e_y = \frac{h}{l} \left[\left(v_1^2 - \frac{h}{r_1} \right) x_1 - (x_{1x} v_{1x} + x_{1y} v_{1y}) v_{1x} \right] \quad (A.13)$$

$$e_x = \frac{h}{l} \left[\left(v_1^2 - \frac{h}{r_1} \right) x_{1x} - (x_{1x} v_{1x} + x_{1y} v_{1y}) v_{1x} \right]$$

$$\begin{aligned} v_{2y} &= v_2 \cos(\theta_2 - \phi_2) \\ v_{2x} &= -v_2 \sin(\theta_2 - \phi_2) \end{aligned} \quad (\text{A.26})$$

$$\begin{aligned} x_{2y} &= x_2 \sin \theta_2 \\ x_{2x} &= x_2 \cos \theta_2 \end{aligned} \quad (\text{A.25})$$

$$\phi_2 = \cos^{-1}\left(\frac{x_2 v_2}{h}\right) \quad (\text{quadrant}) \quad (\text{A.24})$$

$$\theta_2 = \left[\frac{y_0 + y_2}{360^\circ} - \text{INTREGR}\left(\frac{y_0 - y_2}{360^\circ}\right) \right] \cdot 360^\circ \quad (\text{A.23})$$

$$v_2 = \sqrt{2(E + \frac{h}{L^2})} \quad (\text{A.22})$$

$$x_2 = \frac{1 + e \cos y_2}{a(1 - e^2)} \quad (\text{A.21})$$

and k is the number of times the periapsis is passed during the transfer. The rest of the values at point 2 are given by

$$E_2 = \cos^{-1}\left(\frac{1 + e \cos y_2}{e + e \cos y_2}\right) \quad (\text{A.20})$$

where E is the eccentric anomaly, defined by

$$t_{xx} = \sqrt{\frac{h}{a^3}} [2\pi k + (E_2 - e \sin E_2) - (E_1 - e \sin E_1)] \quad (\text{A.19})$$

$$\dot{x}_i = \{ \dot{x}_1, \dot{x}_2, \dot{x}_3 \} \quad (2.5)$$

The above equations will play an important part in the determination of the constraints on the total time-of-flight and the rendezvous requirement. For the time-of-flight constraint, the rendezvous requirement. For the time-of-flight constraint, the times, which are design variables, to the free-fight time as found from Equation A.19. This value must then fall below the specified TOF_{\max} (three years for most cases) for the constraint to be satisfied. For the rendezvous requirement, recall from Chapter 2 that the state vector at point i , x_i , was defined such that

$$\Phi_2 = (1 - \frac{I_{spg}}{a_{02} t_{p2}}) [\ln(1 - \frac{I_{spg}}{a_{02} t_{p2}}) - 1] + 1.$$

$$x_{2y} = x_2 \sin \theta_2 + v_2 t_{p2} \cos(\theta_2 - \phi_2) + \frac{a_{02}}{(I_{spg})^2} \cos(\beta_2 - \theta_2) \Phi_2 \quad (A.28)$$

$$x_{2x} = x_2 \cos \theta_2 - v_2 t_{p2} \sin(\theta_2 - \phi_2) + \frac{a_{02}}{(I_{spg})^2} \sin(\beta_2 - \theta_2) \Phi_2$$

and

$$v_{2y} = v_2 \cos(\theta_2 - \phi_2) - I_{spg} \cos(\beta_2 - \theta_2) \ln(1 - \frac{I_{spg}}{a_{02} t_{p2}}) \\ v_{2x} = -v_2 \sin(\theta_2 - \phi_2) - I_{spg} \sin(\beta_2 - \theta_2) \ln(1 - \frac{I_{spg}}{a_{02} t_{p2}}) \quad (A.27)$$

The equations governing the final powered-flight phase of the trajectory are found by applying coordinate rotation matrices to Equations A.5 and A.10, similar to the way that Equations A.11 and A.12 were obtained. These equations were found to be

quadrant is used when inverse trigonometric functions are used. With the above formulation, care must be taken in the programming of the above equations to assure that the proper quadrant is used when inverse trigonometric functions are used.

$$\begin{aligned} V_x,_{10} &= -V_p \cos \theta_{c,10} \\ V_y,_{10} &= -V_p \sin \theta_{c,10} \end{aligned} \quad (\text{A.33})$$

$$\begin{aligned} X_y,_{10} &= X_p \sin \theta_{c,10} \\ X_x,_{10} &= X_p \cos \theta_{c,10} \end{aligned} \quad (\text{A.30})$$

$$\theta_{c,10} = \theta_2 + \sqrt{\frac{L_p^2}{L_3^2}} \text{TOP} \quad (\text{A.29})$$

The rendezvous constraint requires that $x_{t,EC} = x_{t,10}$, which represents the Emerald City ending the transfer with the desired velocity and radius vectors at the target orbit. The state vector, $x_{t,EC}$, can be found from Equations A.27 and A.28, while the state vector, $x_{t,10}$, can be determined from

ENGINE CHARACTERISTICS CALCULATIONS

APPENDIX B

```

** calculate exit mach number   **
      VTH=SQRT(GAMMAT*UGC*TTH/H2MT)
      &((GAMMAT+1)/(GAMMA-1))/UGC)
      ATH=ATH/SQRT(GAMMAT*H2MT*(2/(GAMMAT+1))**)
      ATH=PDOT*SQRT(TH2)/PRES
      H2MT=H2MT+8.94761E-20*TTH**4
      &2.49052E-14*TTH**3
      H2MT=2.32426-.000111528*TTH+2.53066E-9*TTH**2-
      &6.49491E-29*TTH**6
      GAMMAT=GAMMAT+4.37181E-18*TTH**4-2.65532E-23*TTH**5+
      &3.66763E-13*TTH**3
      GAMMAT=3.84502-.000336982*TTH+1.61689E-8*TTH**2-
      PTH=PRES/((1+(GAMMAC-1)/2)**(GAMMAC/(GAMMAC-1)))
      TTH=TH2/(1+((GAMMAC-1)/2))

** calculate throat conditions   **
      H2MHC=H2MHC+8.94761E-20*TTH2**4
      &14*TTH2**3
      H2MHC=2.32426-.000111528*TTH2+2.53066E-9*TTH2**2-2.49052E-
      &6.49491E-29*TTH2**6
      GAMMAC=GAMMAC+4.37181E-18*TTH2**4-2.65532E-23*TTH2**5+
      &13*TTH2**3
      GAMMAC=3.84502-.000336982*TTH+1.61689E-8*TTH2**2-3.66763E-
      &6.49491E-29*TTH2**6
      calculate hydrogen molecular mass in cavity   **
      VD=UVVC*VC
      VC=1.3333*PI*((DIAM/2)**3)
      calculate hydrogen ratio of specific heats in cavity   **
      TU=140.06*((PRES*THRUST*SPIMP/DIAM)**.16)*(DOTM**.017)
      calculate uranium temperature   **
      H2DOT=PDOT-UDOT
      UDOT=PDOT/(DOTM+1)
      calculate mass flow rate of hydrogen and uranium   **
      PDOT=THRUST/(SPIMP*GRAV)
      PRES=(1066.57*CRITM*((THRUST*SPIMP)**.277)*(DOTM**.1012)/
      &(DIAM**3.277))*1.383
      calculate mass flow rate from nozzle   **

```

```

      ** calculate exit conditions   **
      ** VE=SPIMP*GRAV
      ** TE=H2MNC*(VE/AMACH)**2/(UGC*GAMMA C)
      ** PE=RES/((1+((GAMMAC-1)/2)*AMACH**2)**(GAMMA C)
      ** GAMMA E=1.40018-3.60774E-6*TE-2.87154E-8*TE**2+5.90601E-
      ** 6.12*TE**3
      ** GAMMA E=GAMMA E-2.94162E-16*TE**4
      ** H2MNE=-2.8375E-6*TE+2.01588
      ** RHOU=CRITM/VU
      ** calculate density of uranium   **
      ** DIAMU=2*(3*VU/4/PI)**(.3333333)
      ** QR=((TU/950)**6.25)*DIAMU/PRES
      ** calculate thickness and mass of pressure shell   **
      ** TPHS=PRES*(DIAM+1.52)/(5.516E9)
      ** PSM=1333.33*PI*((DIAM+1.52+2*TPHS)**3-(DIAM+1.52)**3)
      ** calculate mass of moderator, turbopump, nozzle, and
      ** radiator   **
      ** EMN=191.67*PI*((DIAM+1.54)**3-DIAM**3)
      ** TPM=.000307181*H2DOT*((1.5*PRES)**(.66667))
      ** ENM=52861.26*TURBUST/PRES
      ** PR=3E-6*SPIMP+4.4E-2
      ** RM=145*PR*QR
      ** calculate total engine mass   **
      ** ENGMASS=PSM+EMN+TPM+ENM+RM
      ** calculate engine specific mass and jet power   **
      ** ENGMASS=PSM+EMN+TPM+ENM+RM

```

```

**      CALCULATE thrust to weight ratio   **
      VEXIT=SPIMP*GRAV
      ALPMA=204.96*ENGMASS/(SPIMP*THRUST)
      PJET=5*THRUST*SPIMP*GRAV/1E6
      **      CALCULATE exit velocity   **
      PRES=PRESS/ATM
      WRITELINE(1,70)
      FORMAT(, SPECIFIED VALUES:,)
      WRITELINE(1,80) SPIMP,THRUST,VUVC,DIA
      FORMAT(1X, ISPD=,F8.2,, SECONDS,,3X, THRUST=,F11.2,, METERS,,)
      NEWTONS,,3X, VU/VC=,F3.2,3X, DC=,F5.2,, METERS,,)
      WRITELINE(1,90)
      FORMAT(//,1X, CALCULATED ENGINE PARAMETERS:,)
      WRITELINE(1,100)
      FORMAT(1X, ENGINE CAVITY CONDITIONS:,)
      WRITELINE(1,110) TH2,TU
      FORMAT(1X, T(H2)=,F8.2,, KELVIN,,19X, T(U233)=,F9.2,,)
      WRITELINE(1,120) PRES,CRTM
      FORMAT(1X, CAVITY PRESSURE=,F7.2,, ATM,,13X,
      & ,CARTICAL MASS U233=,F6.2,, KG,,)
      WRITELINE(1,130) VC,VU
      FORMAT(1X, CAVITY VOLUME=,F5.2,, CUBIC
      & METERS,,8X, URANIUM
      & VOLUME=,F5.2,, CUBIC METERS,,)
      WRITELINE(1,140) DIAU,RHOU
      FORMAT(1X, URANIUM DIAMETER=,F4.2,, METERS,,12X, URANIUM
      & DENSITY=,F6.2,, KG/CUBIC METER,,)
      WRITELINE(1,150) HZMC,GAMMA
      FORMAT(1X, HYDROGEN MOLECULAR
      & MASS(CAVITY)=,F5.3,2X, GAMMA(CAVITY)=,F5.3)
      WRITELINE(1,160)
      FORMAT(1X, MASS FLOW RATES:,)
      WRITELINE(1,170) DOTM,PDOT
      FORMAT(1X, H2-T0-U233 MASS FLOW RATE=,F7.2,,6X,
      & PROPELLANT MASS FLOW RATE=,F6.2,, KG/SEC,,)
      WRITELINE(1,180) HZDOT,UDOT
      FORMAT(1X, H2 Mass FLOW Rate=,F7.3,, KG/SEC,,6X,, U233
      & MASS FLOW Rate=,F6.3,, KG/SEC,,)
      WRITELINE(1,190)
      FORMAT(1X, ENGIN DIMENSIONS:,)
      WRITELINE(1,200) THPS,PSM
      FORMAT(1X, PRESSURE SHELL THICKNESS=,F5.3,, METERS,,)
      WRITELINE(1,210) EMM
      FORMAT(1X, MODERATOR THICKNESS=,F9.2,, KG,,)
      WRITELINE(1,220) TPM,ENM
      WRITELINE(1,230)

```



```

360   write(1,360) f(i)
      format(1,350)x,const
      write(1,350)x,lambda
      format(1,15.9,5x,constant=,f20.4)
      const=top/bottom
      bottom=h2dot*3.7*(1+(gammae-1)/2*mach**2)**.5*(2/
     & (gammae+1))**((gammae+1)/2/(gammae-1))
      top=f(i)*qr*6.448e+7*(h2me*pe/te/82.06)*mach*b*
     & l)**(1/(gammae-1))
      b=x/4/sqrt(pi)*(gammae-1)/(gammae+1)**.5*(2/(gammae+
     & 1)**(1/(gammae-1)))
      top=e(i)*qr*6.448e+7*(h2me*pe/te/82.06)*mach*b*
     & l)**(1/(gammae-1))
      bottom=h2dot*3.7*(1+(gammae-1)/2*mach**2)**.5*(2/
     & (gammae+1))**((gammae+1)/2/(gammae-1))
      write(1,350)x,lambda
      format(1,15.9,5x,constant=,f20.4)
      const=top/bottom
      bottom=h2dot*3.7*(1+(gammae-1)/2*mach**2)**.5*(2/
     & (gammae+1))**((gammae+1)/2/(gammae-1))
      top=f(i) e(t)=,f10.7
      format(1,x,e(t)=,f10.7)
      write(1,360) f(i)
      close(unit=1)
      enddo
      end
      stop
      end

```

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